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RF Power Amplification Using a High Voltage, High Current IGBT

New insulated gate bipolar transistors offer some amazing power amplifier capabilities, as the author's experiments show.

This article describes experiments, calculations, modeling, and analysis of a specific insulated gate bipolar transistor (IGBT) device. Originally, a casual examination of datasheets turned up several recently available IGBTs in one device family that looked surprisingly capable of very high peak RF power and amplification at useable average power levels, if both the maximum voltage and current capabilities of the device could be used simultaneously. Figure 1 shows three International Rectifier transistors, along with a 360 V dc power supply.

Given their moderate internal device parasitic element makeup, and charge supply requirements to the IGBT gate, circuit design using these bipolar junction devices additionally looked attractive. In fact, the AUIRG4045D, as the smallest device in the family, is rated at 600 V and 6 A. It comes in a diminutive D-Pak package (costing about a dollar each in lots of 100). This transistor proved capable of delivering 3342 W of pulsed power into a 50 Ω load at 20 MHz when driven by 3 or 4 W with no reactive input current correction.[1] See Figure 2.

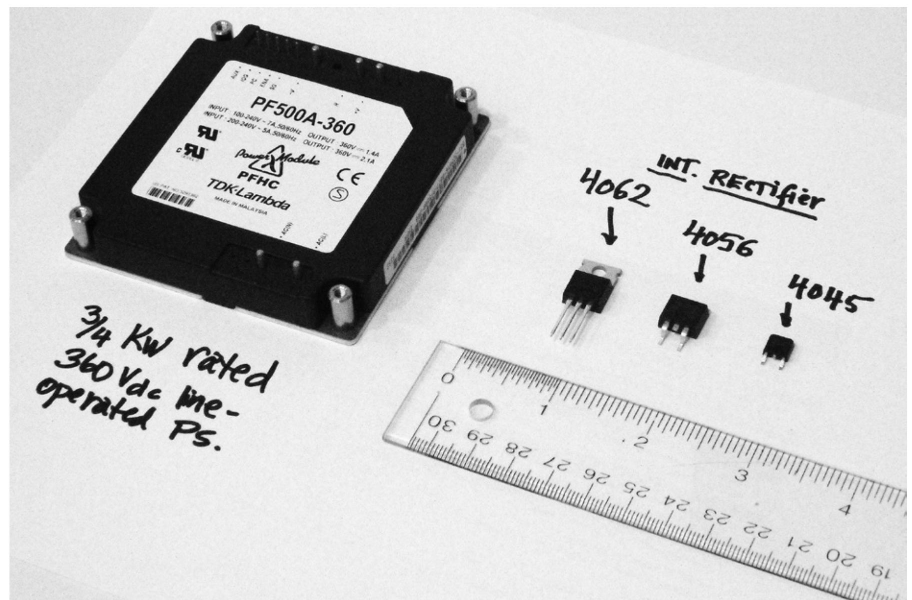


Figure 1 — This photo shows a 360 V dc power supply used in these experiments along with a family of International Rectifier insulated gate bipolar transistors (IGBT) evaluated for the experiments.

The sine wave output to the 50 Ω (actually 48 Ω) load as shown in Figure 3 has been attenuated by 4.9 dB to protect the Tektronix high voltage probe from damage — the actual voltage is 1133 $V_{p\text{-}p}$, which corresponds to 400.5 V_{rms} across the 48 Ω load. That is an output power of 3342 W, with a second harmonic component of –30 dBc = 3.3 W.

The important takeaway here is the somewhat squared-up shape of the IGBT collector voltage waveform shown in Figure 4, which occurs as a result of overdriving this Class A amplifier with a 20 MHz square wave. Since the average power output capability of the device is what counts for Amateur Radio work, what we want to do with these devices is to get the efficiency up. The goal is to shape the collector voltage and current waveforms, so that regions of higher voltage in the collector RF waveform correspond with low current in the IGBT and vice versa.

It can be readily shown that a linear Class A amplifier with transducer efficiency approaching 100% is possible using a square wave input. In this regard, if the Pi network in the present circuit is replaced with a network that in effect terminates the IR4045 collector with 22 Ω of resistance at odd harmonics (f_0, 3 f_0, 5 f_0, and so on) efficiency here will improve and the IR4045 can then operate without ever saturating or

[1]Notes appear on page 20.

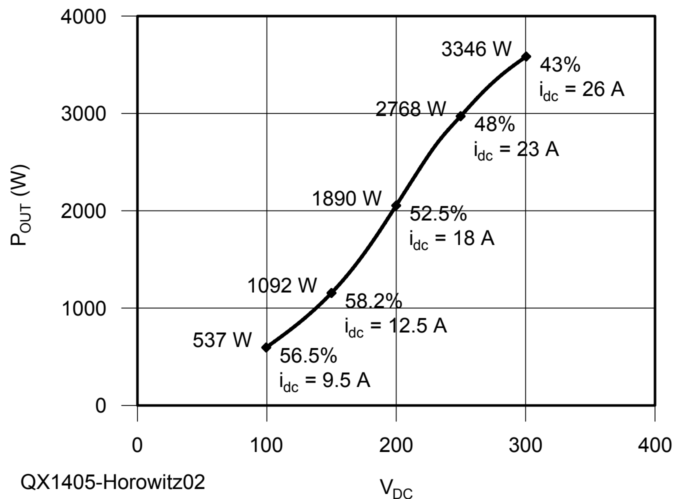


Figure 2 — This graph shows the measured power output of a single AUIRGR4045D IGBT device as an RF amplifier with 20 MHz bursts.

pulsed power also at the 200 W average power level when the dc to RF conversion efficiency is 50%. The high device current capability is not used when not operating at high peak power, however the high voltage property alone may be useful for simplifying circuit designs. Design tradeoffs including cost in comparing IGBTs here with MOSFETs for narrowband use should be done.

Initially reading the manufacturer's documentation turned up statements such as "Ultrafast 8 -30 kHz," and "Application — Air Conditioning Compressor;" hence I decided to buy the smallest version, and to first run a frequency response sweep of the device transconductance. In fact when I first powered it up, the device oscillated strongly at 200 MHz. (That was an exciting moment!) I immediately worked to find simple stabilization methods — a small ferrite ring core or two around the wire to the gate terminal or a 10 Ω resistor in series with the gate. (This was lossy; I did not subsequently use this technique, and it is not necessary at high power levels.)

High peak RF power (watts per pulse) of itself in a transistor or diode is not generally useful; technically sophisticated device modalities, such as TRAPATT action using a 1N5408 diode produces high pulsed power periodic transients at no significant energy (joules) or average power (average watts = joules/pulse × pulses/second) levels. A TRAPATT diode is a PN junction diode, similar to the IMPATT diode, but characterized by the formation of a trapped space-charge plasma within the junction region; it is used in the generation and amplification of microwave power. The name is derived from the description: trapped plasma avalanche transit time diode.

having to turn off on part of each RF cycle (it does both now because of overdrive).[2] The bipolar IR4045 has large 20 MHz RF Power capability, but is not a 20 MHz switch and stores some excess charge near saturation.

Interestingly, this device can also deliver high average power at very high peak power levels, partly because the 4045 has meaningful heat capacity in addition to thermal conductivity when the energy comes in short bunches. This can be elicited by re-labeling the device safe operating area (SOA) curves in joules per pulse, and in interval; and also by examination of the transient thermal impedance curves shown in Figure 25 on the manufacturer's data sheet.[3] When energy is dissipated more continuously, only the thermal conductivity is involved.[4] Figure 5 exemplifies such a situation for a clocked 10 kHz pulse train, where average power above 50 W is maintained for pulse powers up to 5 kW at 50% dc to RF conversion efficiency. The largest device in this family, which has a price tag of $3.33 each in 100 piece lots, calculates out to be able to deliver over 200 W CW and many kilowatts

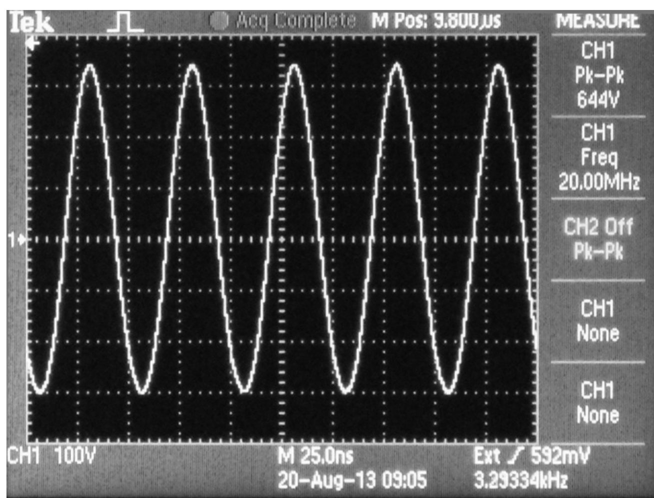


Figure 3 — This oscilloscope pattern shows the output from a single AUIRGR4045D IGBT device, with the signal attenuated 4.9 dB across a 48 Ω load. The second harmonic is –30 dBc (3.3 W).

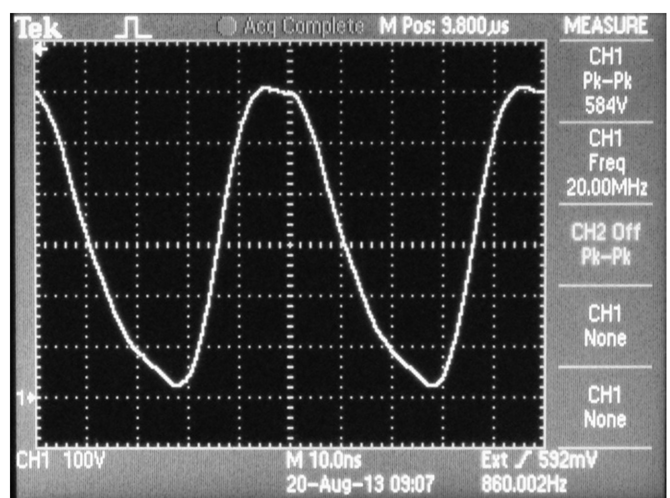


Figure 4 — This oscilloscope pattern shows the voltage waveform across the collector to emitter terminals of the single AUIRGR4045D device.

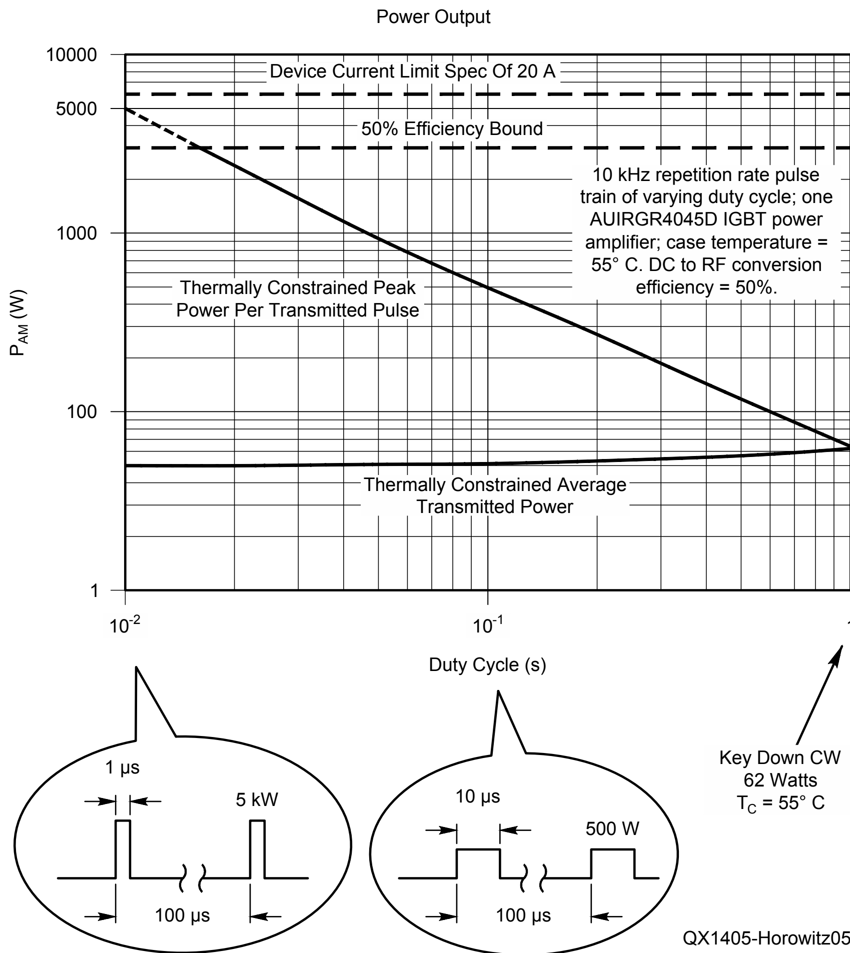


Figure 5 — This graph plots the peak power per transmitted pulse and average power for a 10 kHz repetition rate pulse train of varying duty cycle.

IMPATT diodes with heat sinks, for example, are capable of delivering 3 kW CW at 3 GHz and higher frequencies as oscillators, but have high phase noise and also cannot amplify. There are useful applications for these sorts of high power devices, but not typically in Amateur Radio, where for example, Gunn diodes operating at low CW powers are familiar for microwave work.

Once a device can amplify and then deliver average power it potentially becomes useful for communication systems, minimizing bandwidth to use spectrum space efficiently.

The Experimental Hardware and Design

The hardware shown in Figure 6 consists of the IGBT device and driver pair on the center whiteboard containing the large Pi network. The dc pulsed power source and RF amp bias supply (Instek Power Supply) are shown in black polyethylene boxes towards the right side of the photo. At the back, starting from the left, there is a Rigol waveform generator, a Tektronix oscilloscope in the center, and an Instek triple output dc power supply — also used to supply 20 V dc to the RF driver device. I also used a Tektronix P5100A high voltage/ high frequency/ high impedance scope probe.

This layout forms my test setup. Figure 7 shows a close-up shot of the Pi network and RF head. Figure 8 shows a close-up of the high voltage power supply for driving the RF head. Hopefully this setup will be flexible

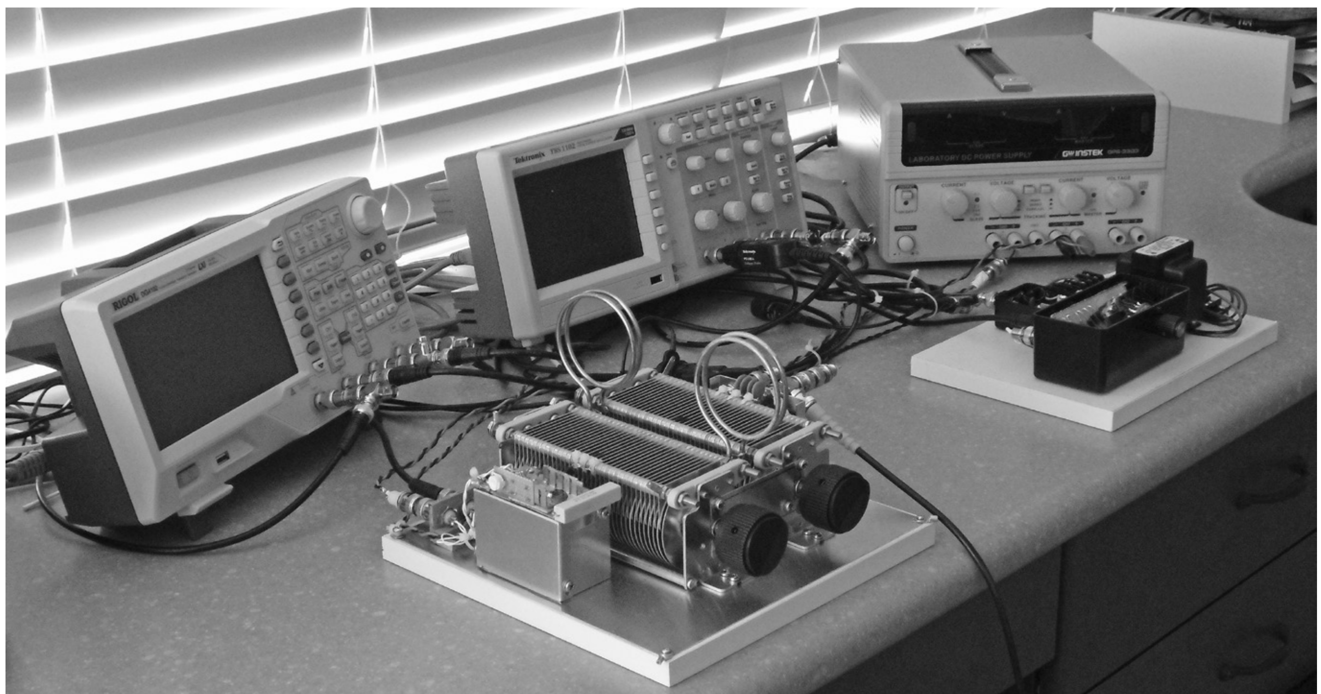


Figure 6 — This photo shows the test setup for the experiments.

enough to accommodate different devices and operating modes as they "suggest themselves." Figure 9 is a schematic diagram of the hardware test setup.

Output Network and 10 kW Pulsed Power Supply

The Pi network and inductor feed along with bypass capacitors and voltage divider output (to protect the high voltage Tektronix probe from damage) have an aggregate unloaded *Q* of 350, which is necessary to keep power losses below 100 W at the 3.3 kW operating level here with resistive ratios below 10 to 1. The present Pi network is capable of greater than 10 kW output.

The pulsed power supply is capable of about 10 kW output at 300 V regulated for 100 μs pulses. At lower output voltages, power capability is correspondingly reduced because of increased power dissipation and transient thermal limits within the AUIRGDC0250 series pass transistor.

RF Driver Design

A 6 W capable laterally diffused metal oxide semiconductor (LDMOS) transistor with f_t = 7 GHz is used as a source follower to present a 3 Ω drive resistance to the IGBT gate out to 150 MHz. This is used to control the effect of harmonic currents generated by the nonlinear charge versus gate voltage transfer property of the IR4045.

The low impedance drive also insures stable amplification by the IGBT. The LDMOS operates at low quiescent dc current, but can produce high current positive RF pulses, which drive the IGBT effectively. The LDMOS transistor used here can be operated at an average power of 3 W or so, and supply adequate drive to result in IGBT 3.3 kW P_{out} levels at 20 MHz.

The 7 GHz LDMOS transistor circuit, though very simple, needs to be constructed with microwave components to avoid instability. Measurement gear may not indicate such high frequency oscillations, but their existence can be readily monitored during use by the dc current draw. As used here, the device dc current drain never changes value despite the wide variation in drive levels (milliwatts to watts) because the pulsed input square wave duty cycle is low.

There is no need to correct the reactive input current to the IGBT, since its power gain of 1000 or so allows the designer the freedom to tailor the drive waveform to help achieve higher efficiency amplification. The Rigol DG4102 Arbitrary Waveform Generator can, in principle, be used to synthesize a waveform point by point to drive the IGBT gate in pursuit of higher RF efficiency

Shielding to Control High Level RF Fields

It is necessary to deal with the high local field strengths to avoid upsetting measurements and the low level circuitry; the 150 pF bypass capacitor from the base to emitter of the 2N3904 suffices in this system. The pictures of the test bed (Figures 6 and 7) have been photographed with the P5100A probe shield removed.

Figure 10 is a photo of the shielded TEK P5100A high voltage probe used to make accurate RF power output measurements in the presence of the strong ambient RF field. I added this aluminum box to the test setup when I realized that the plastic-encased high voltage probe may have been affected by the RF field generated by the amplifier.

Gate Protection Circuitry

I stripped out all of the gate protection circuitry in the interest of speedy testing. For

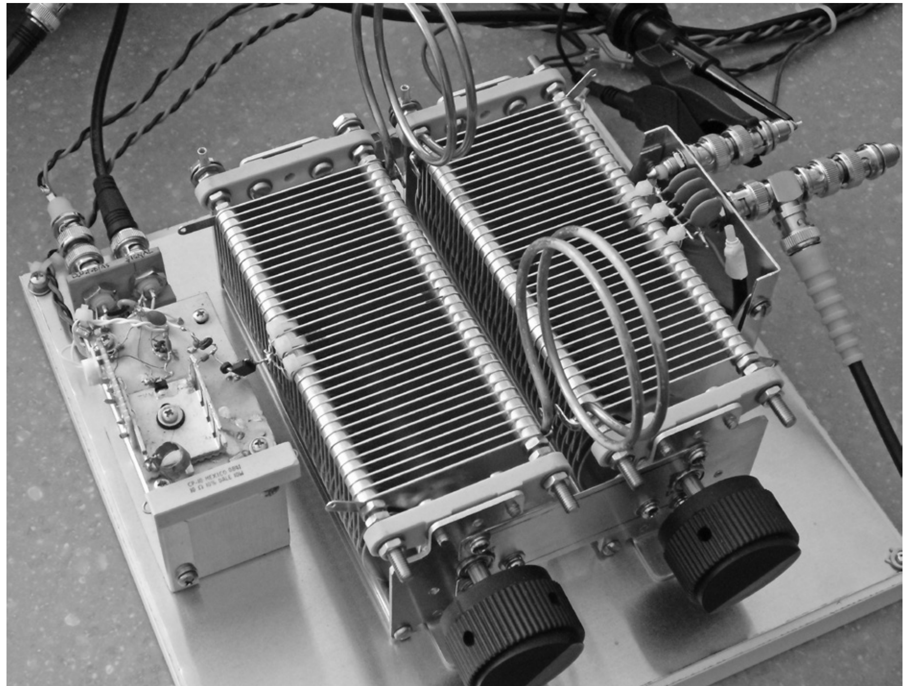


Figure 7 — Here is a close-up view of the Pi network and RF head assembly.

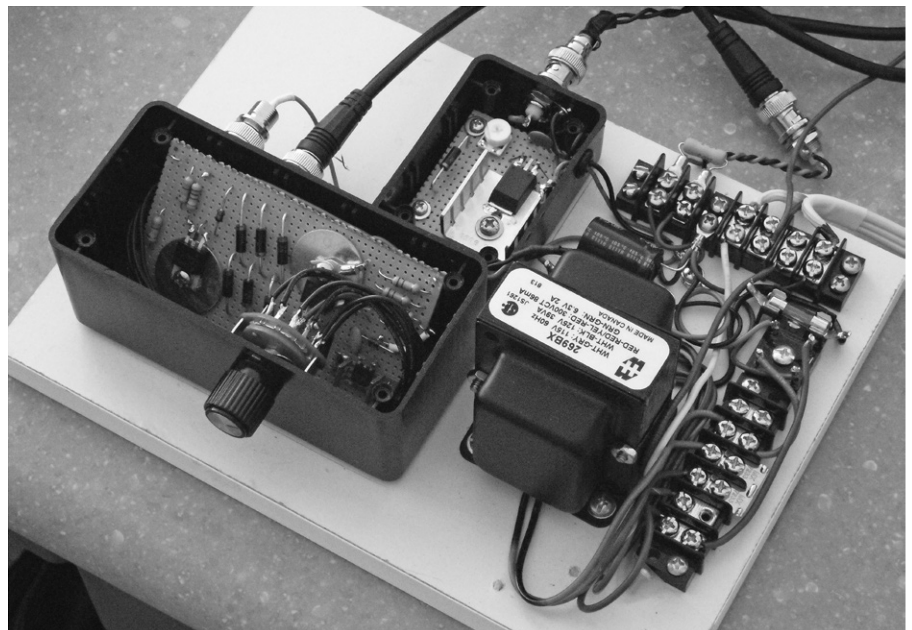
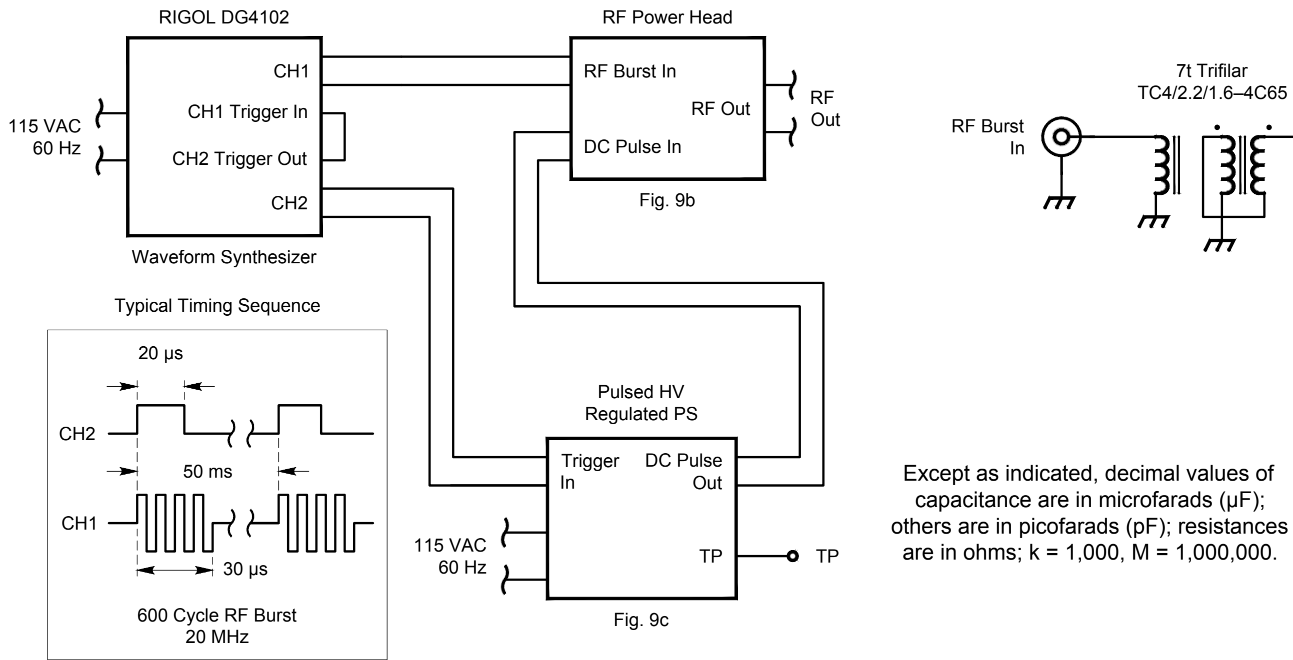


Figure 8 — This photo shows a close-up view of the 10 kW pulsed power supply for the IGBT RF head.



Except as indicated, decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); resistances are in ohms; k = 1,000, M = 1,000,000.

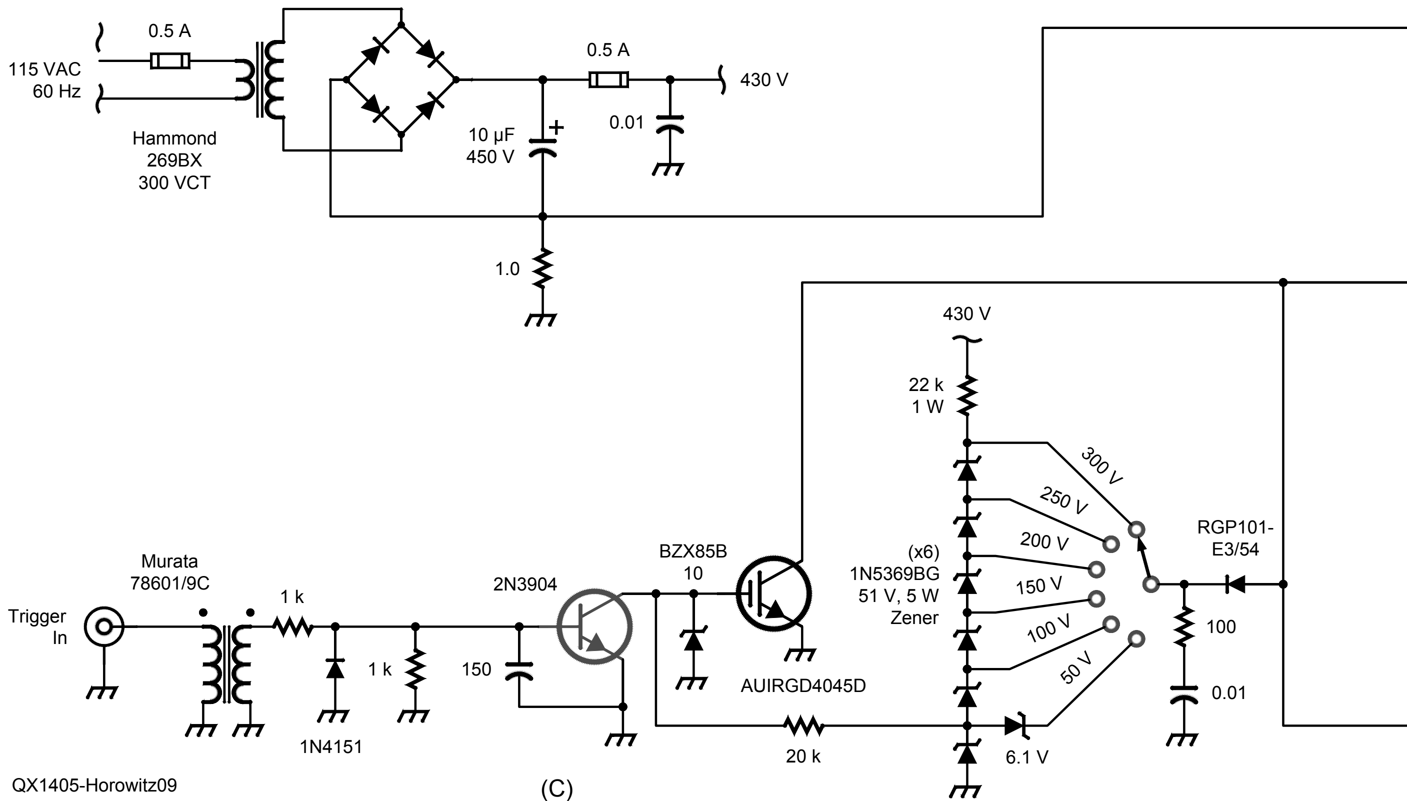
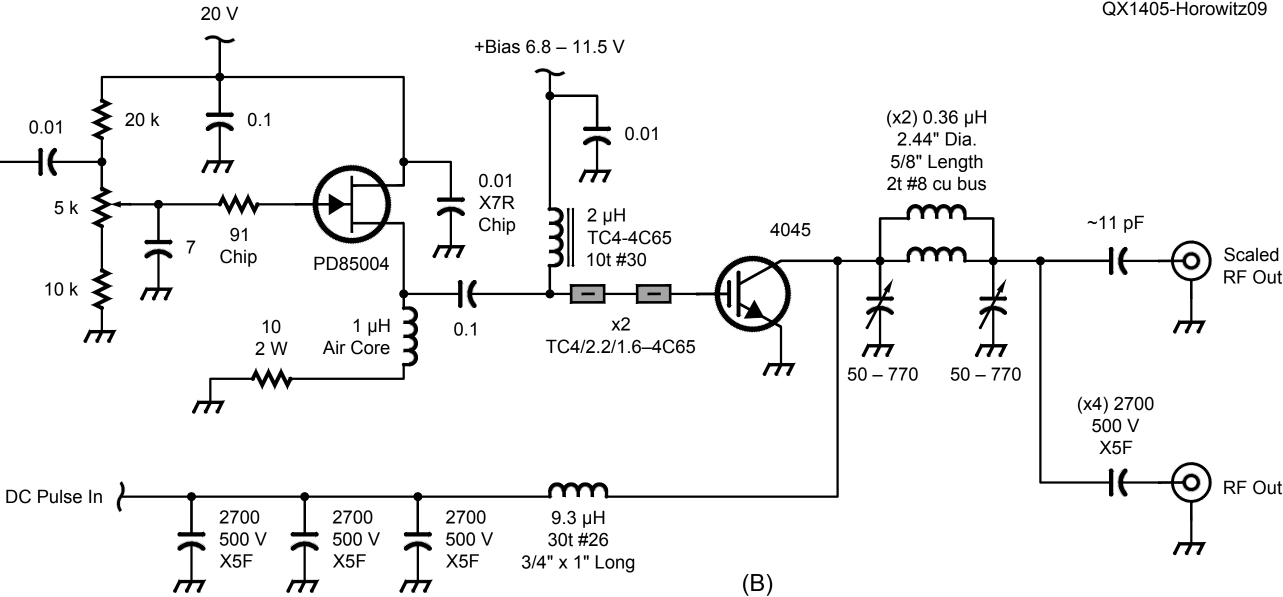
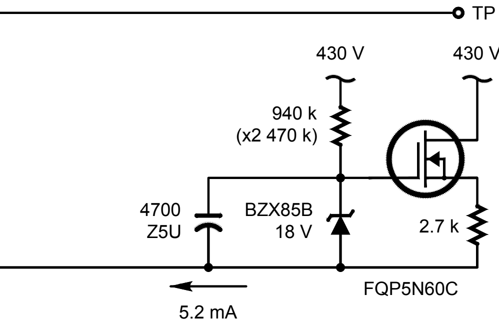
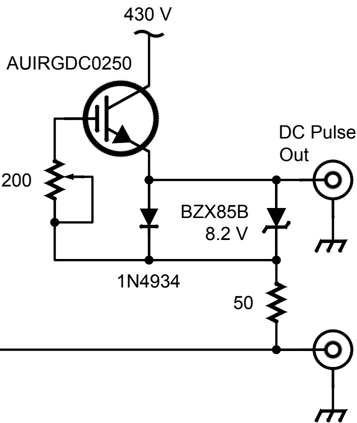


Figure 9 — Here is a detailed schematic diagram of the IGBT RF amplifier test setup.


QX1405-Horowitz09
20 V
+Bias 6.8 – 11.5 V
0.01
20 k
0.1
0.01
(x2) 0.36 µH
2.44" Dia.
5/8" Length
2t #8 cu bus
0.01
X7R
Chip
5 k
91
Chip
7
PD85004
10 k
2 µH
TC4-4C65
10t #30
4045
~11 pF
Scaled
RF Out
10
2 W
1 µH
Air Core
0.1
x2
TC4/2.2/1.6–4C65
50 – 770
50 – 770
(x4) 2700
500 V
X5F
RF Out
DC Pulse In
2700
500 V
X5F
2700
500 V
X5F
2700
500 V
X5F
9.3 µH
30t #26
3/4" x 1" Long
(B)


TP
430 V
430 V
940 k
(x2 470 k)
4700
Z5U
BZX85B
18 V
2.7 k
5.2 mA
FQP5N60C


430 V
AUIRGDC0250
DC Pulse
Out
200
BZX85B
8.2 V
1N4934
50

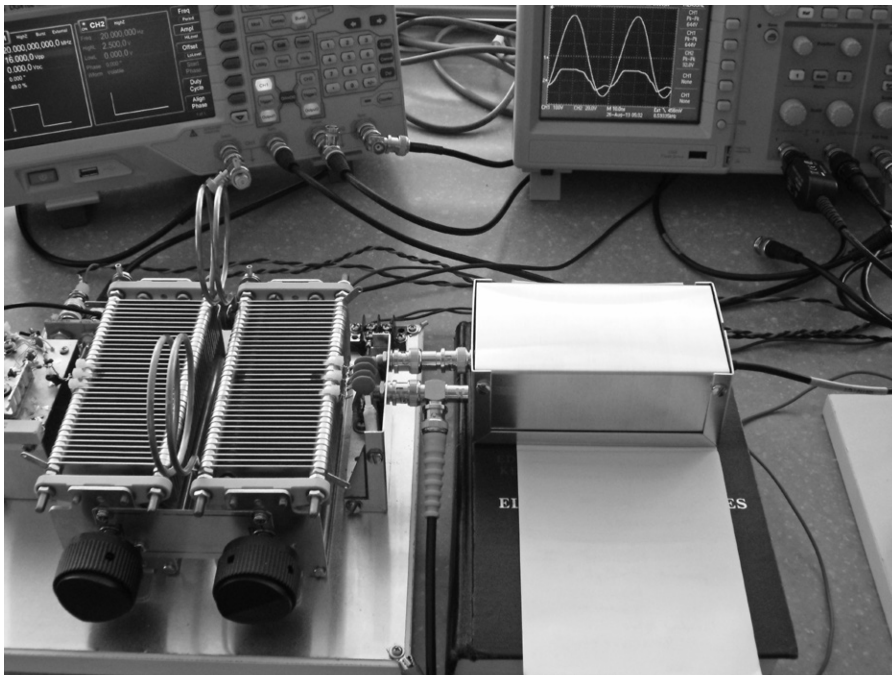


Figure 10 — This photo shows the shielded TEK P5100A high voltage probe used to make accurate RF power output measurements in the presence of the strong ambient RF field.

example, burnouts are quick to troubleshoot when there is a minimum of solid state devices in the circuit. I have not had gates or devices damaged in assembly or tests lately, when the tests have been done with methodical care and attention because the system operation now is familiar to me.

Input Reactive Drive Power Calculation Method

To calculate the input reactive drive power for the IR4045, refer to the manufacturer's data sheet Figure 24. Extend the curve to span –20 to +20 V. This corresponds to charge levels of –7.3 to +16.2 nanocoulombs. Integrate VdQ over this trajectory. At 20MHz this is 100 nanocoulomb volts times 20 MHz = 2 W. A lot of this reactive power can be recovered on the return trajectory with the 1 μH inductor shown in Figure 9 from the PD85004 LDMOS Source to 10 Ω 2 W resistor.

Acknowledgement

Dave Brougham of Fourth Dimension Engineering, Columbia, Maryland did the wideband Spice simulations of the PD85004 LDMOS driver circuit.

Peter Horowitz is an ARRL Member who founded EVI, Inc in 1983. This is a high-tech business specializing in communications systems. He earned a BS in Electrical Engineering from MIT and an MS in Electrical Engineering from New York University. His specialties include RF communications, acoustics and magnetics, prototype hardware design and thick film hybrid manufacturing. He has written many technical articles and contributed to several books, including The Art of Electronics *by Paul Horowitz and Winfield Hill, Cambridge University Press. He holds several patents. Pete is a member of the Columbia Amateur Radio Association, Columbia, Maryland.*

Notes

[1]This data point and the 2.76 kW point, Figure 2, involve RF collector currents considerably exceeding the manufacturer's bound of 20 A for the 4045: There is no data on the datasheet for I_c > 20 A, however the manufacturer's Figure WF.4 does indicate greater capability. The 20 A bound is probably for long term device reliability; we never saw any evidence of P_{out} degradation at the 3.3 kW level, even after hours of continuous pulsing.

[2]D. M. Snyder, "A Theoretical Analysis and Experimental Confirmation of the Optimally Loaded and Overdriven RF Power Amplifier," *IEEE Transactions on Electron Devices*, Volume ED-14, No. 12, Dec 1967.

3 The data sheet for the 4045 transistor is available for download at: **www.irf.com/product-info/datasheets/data/irgr4045dpbf.pdf**.

[4]This description perhaps oversimplifies the situation to some extent. For example, the 4062 manifests somewhat more complicated behavior, as can be also seen in general from transient thermal impedance models among the members of this group.