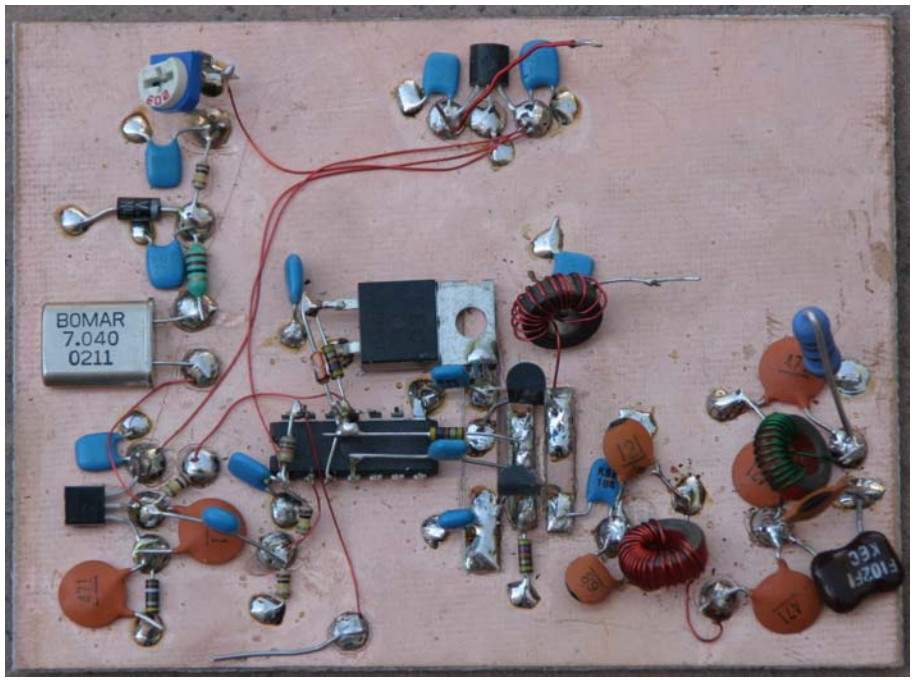
Class E Amplifiers

Part 1: Class E Basics



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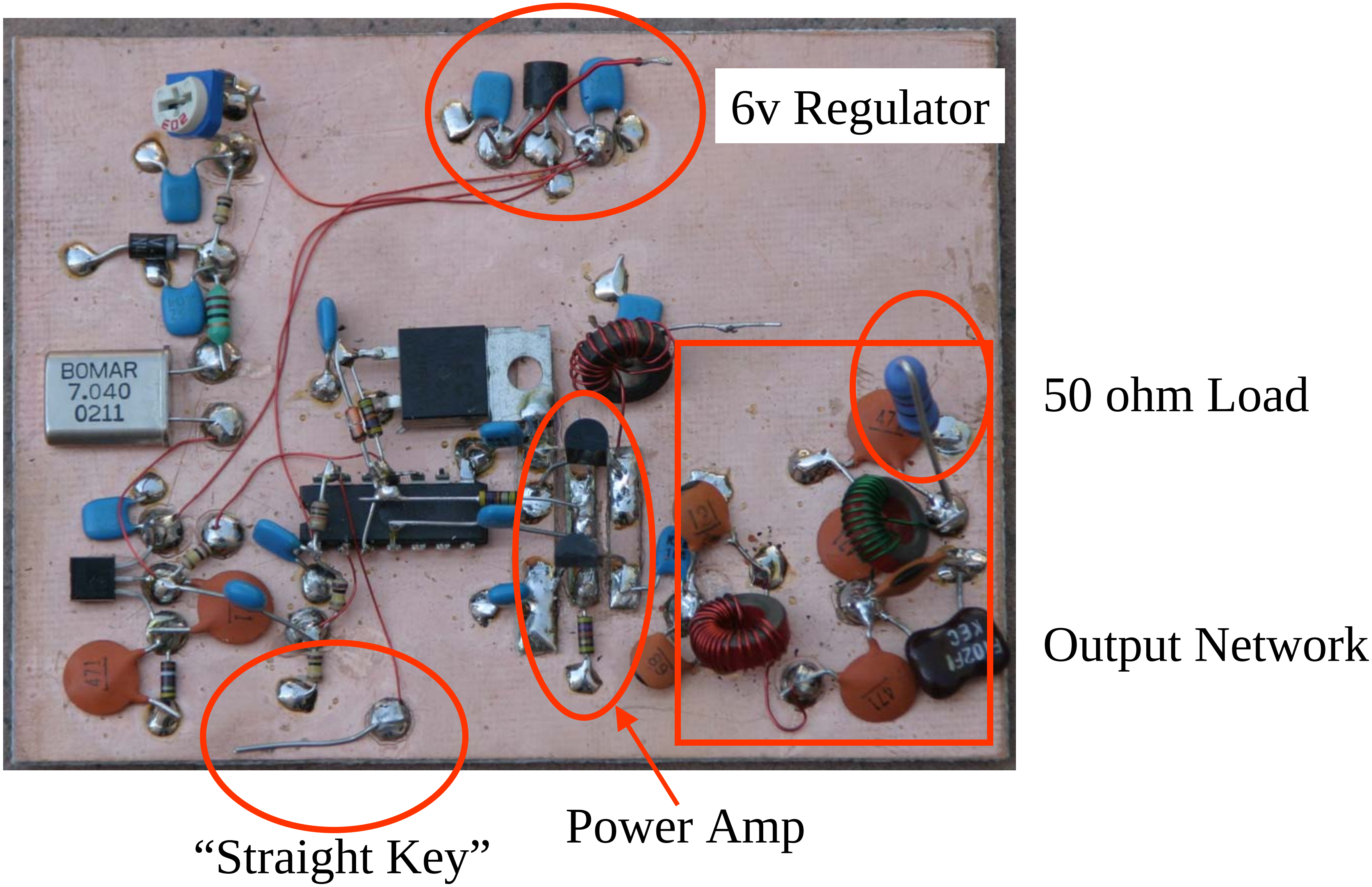
5w Class E 40m Prototype



Why Class E?

Class C final, 2w

40 to 45% efficient, **~ 370 to 410 ma***

Class E final, 2w

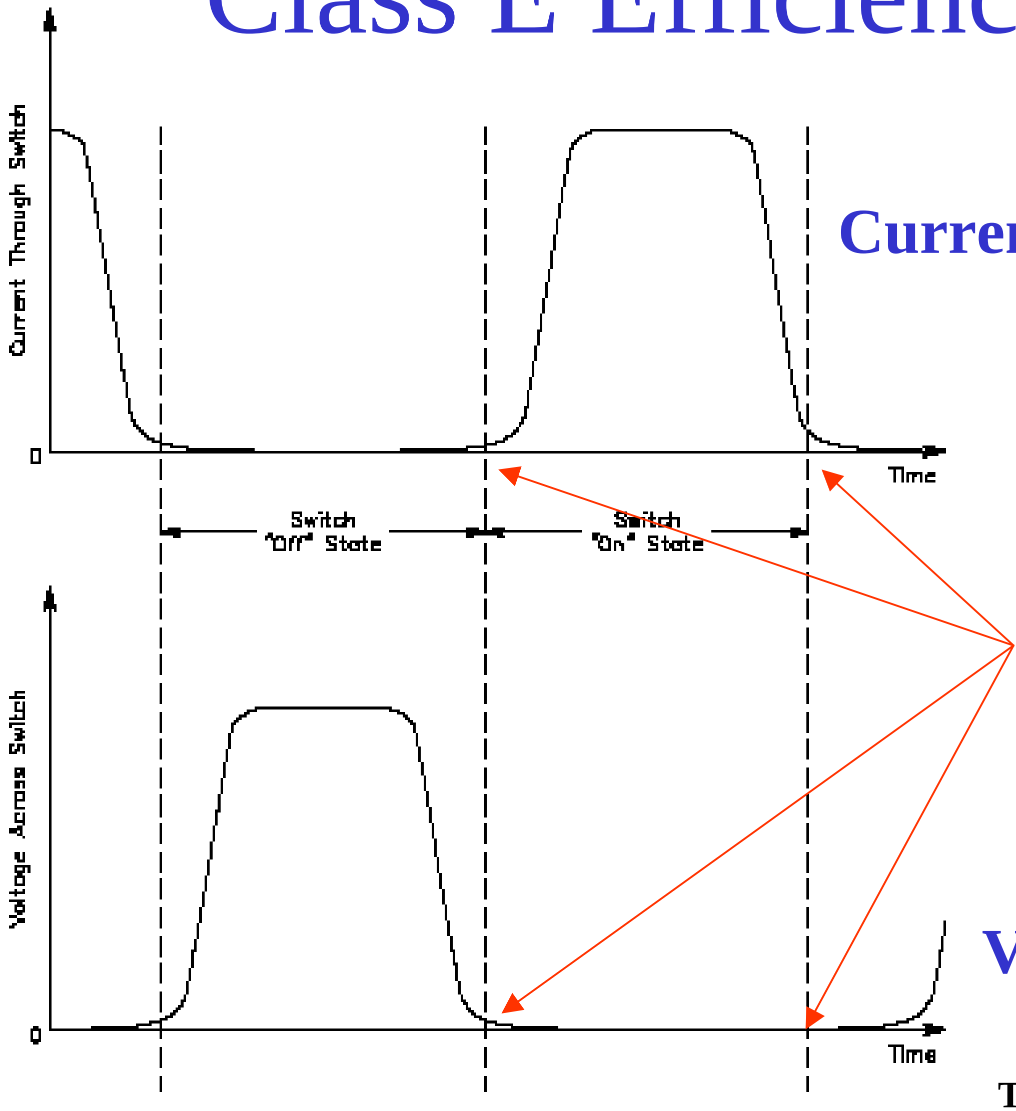
88% efficient, ~ **190 ma***

Almost 50% less TX current required…

Very battery friendly!

**** Does not include PA driver. Class E can require very little driver power!***

Class E Efficiency Secret



Current vs. time

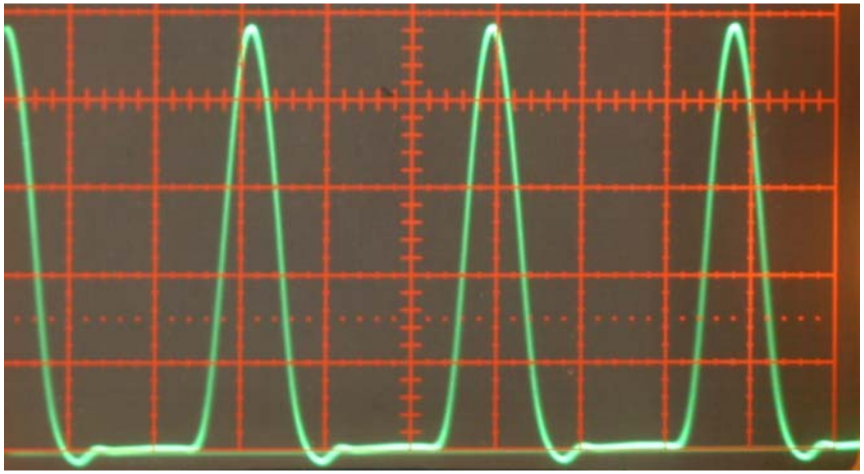
Switch at low current, Low voltage points ~Zero power at switch!

Voltage vs. time

Taken from QEX Jan/Feb 2001

Fig 1—Conceptual "target" waveforms of transistor voltage and current.

Class E Drain Voltage Waveform



Scale 10v/division
~ 48v at peaks for 5 w, ~40v for 2w
For comparison, Class C devices run only 24v peaks

Class E Design Spread Sheet, 7 MHz

QEX Jan/Feb 2001 Class E Design Equations

Class E Output Network Calculator

QL must be larger than 1.788. Normally, Q<5.

User Inputs | **User Outputs**

Input Data				Output Data								
P (watts)	Vcc-Vo	Fo (Hz)	QL	C1 (pf)	L1 (uh)	L2 (uh)	C2 (pf)	R Load	XC1	XL1	XL2	XC2
2.25	10	7.00E+06	2.92	243	66	1.36	748	20.5	93.8	2900	59.8	30.4

Set XL1 above larger than:

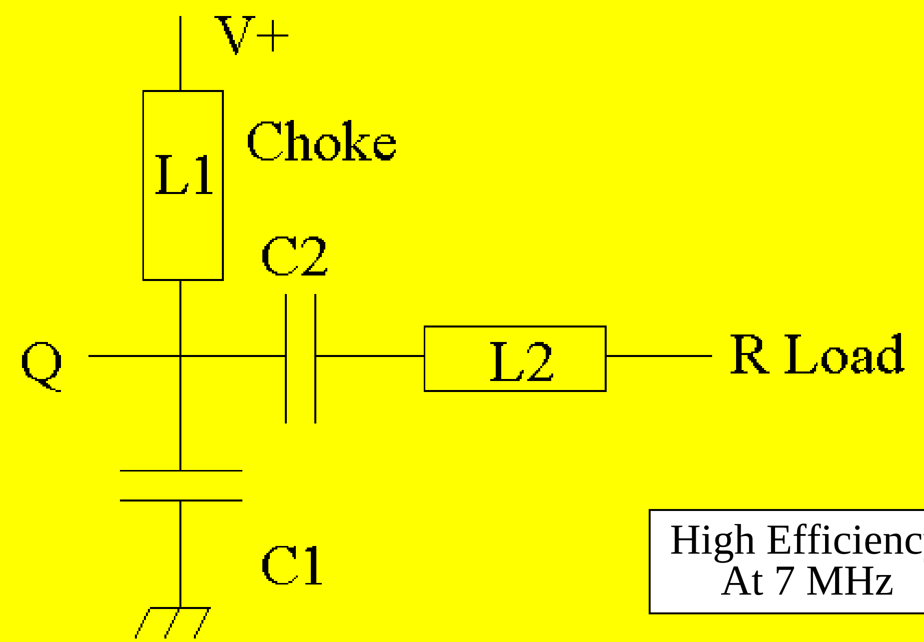
2813

L1 FT37-43		L2 T37-2	
Al	Turns	Al	Turns
420	12.5	40	18.4

Note: Need to Subtract Transistor output C from C1

Trans Cout Fix	
Qc	New C1
20	223

Efficiency Estimate - 2x BS170		
Ron (ohm)	tf (nsec)	Efficiency
1	15	87%



High Efficiency
At 7 MHz

Use Q and exact Power to get C1, L2, C2 to standard values

Class E Design Spread Sheet, 14 MHz

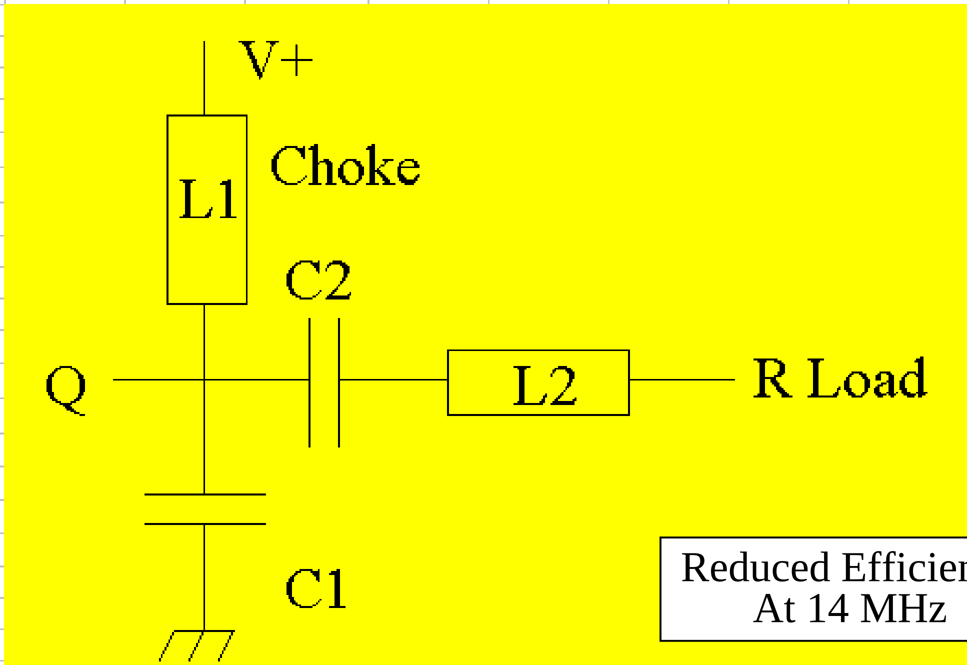
QEX Jan/Feb 2001 Class E Design Equations

Class E Output Network Calculator

QL must be larger than 1.788.   Normally, Q<5.

User Inputs | **User Outputs**

Input Data				Output Data								
P (watts)	Vcc-Vo	Fo (Hz)	QL	C1 (pf)	L1 (uh)	L2 (uh)	C2 (pf)	R Load	XC1	XL1	XL2	XC2
2.25	10	1.40E+07	2.92	121	33	0.68	374	20.5	93.8	2900	59.8	30.4



Set XL1 above larger than:

2813

L1 FT37-43		L2 T37-2	
Al	Turns	Al	Turns
420	8.9	40	13.0

Note: Need to Subtract Transistor output C from C1

Trans Cout Fix	
Qc	New C1
20	101

Efficiency Estimate - 2x BS170		
Ron (ohm)	tf (nsec)	Efficiency
1	15	69%

Reduced Efficiency
At 14 MHz

Lower efficiency at 14 MHz – 69% Predicted

Class E Design Spread Sheet

Excel spread sheet equations…

C1 (pf) = (1e12/(J8*34.2219*D8))*(0.99866 + 0.91424/(E8)
-1.03175/(E8*E8)) + 0.6/(2*2*3.14*3.14*D8*D8*G8/1000000)

C2 (pf) = (1e12/(J8*2*3.14*D8))*(1/(E8-0.104823))
*(1.00121 + 1.01468/(E8 - 1.7879))
-0.2/(2*2*3.14*3.14*D8*D8*G8/1000000)

L1 (uH) = 1000000*L8/(2*3.14*D8)

L2 (uH) = 1000000*J8*E8/(2*3.14*D8)

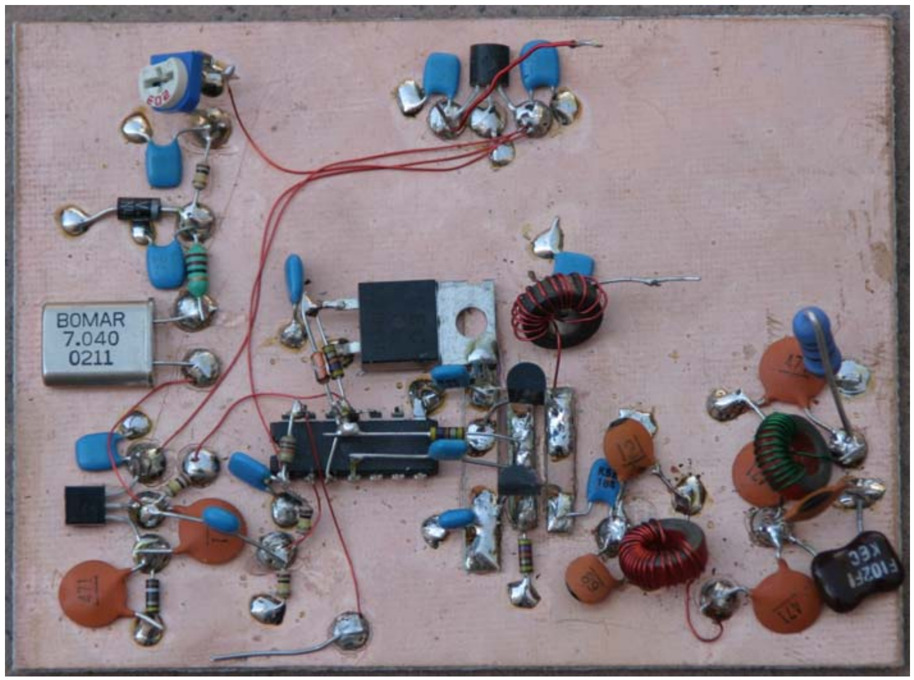
Rload = (C8*C8/B8)*0.576801*(1.001245 - 0.451759/E8 - 0.402444/(E8*E8))

XL1 >= 30*K8

Efficiency = J8/(J8+1.365*K27) -0.01
- (1+ 0.82/E8)* (1+ 0.82/E8)*4*PI()*PI()*D8*D8*L27*L27*1e-18/12

Class E Amplifiers

Part 2: No Tune, Goof Proof Class E Amps



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Problems with Class E QRP Amps

- ***"Tuning" required to get good efficiency***
  - Poor "out of the box" power and efficency
  - Typical to "tweak" output network coils for best power/efficiency
- ***Class E finals fail when presented with low impedance loads***
  - Low impedance loads cause PA to draw too much current and burn up
- ***Inexpensive QRP Class E final rated to only 60v (2N7000)***
  - Typical PA drain voltage operates in the 40 to 50v range w/ 12v supply
  - Improper antenna mismatch can raise drain voltage, blow the PA
    - ***15v supply used with a 12v design could cause problems***
- ***Class E Amps can be unstable into poorly matched loads***
  - Tends to "take off"
  - Can lead to device failure

Class E Tuning Problem

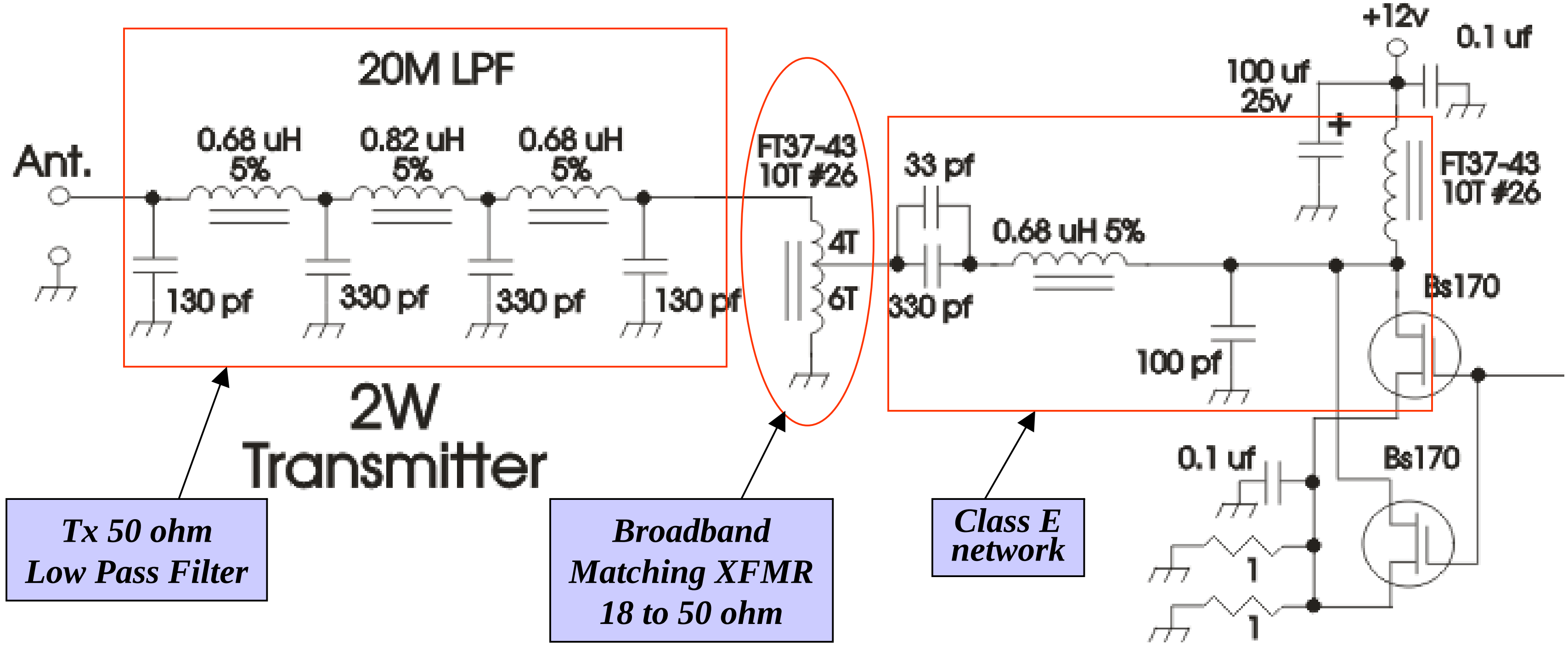
- ***Class E matching network typically presents a reactive load***
    - I.e., the Class E PA output impedance is ***not*** purely resistive
    - Reactive characteristic key to Class E efficiency

- ***QRP Class E networks need loads in the 10 ohm to 50 ohm (5w to 1w) range***
    - Matching network normally needed to transform to 50 ohm load
    - ***1 watt 12v final is a design "sweet spot" – no matching needed***

- ***L/C matching networks are typically used to transform driver impedance to 50 ohm load impedance.***
    - This approach does not work well with a reactive drive source!
    - Leads to frequency specific matching network
    - Variations in driver network and matching network elements force the need for "tuning" of the matching networks

No Tune Class E

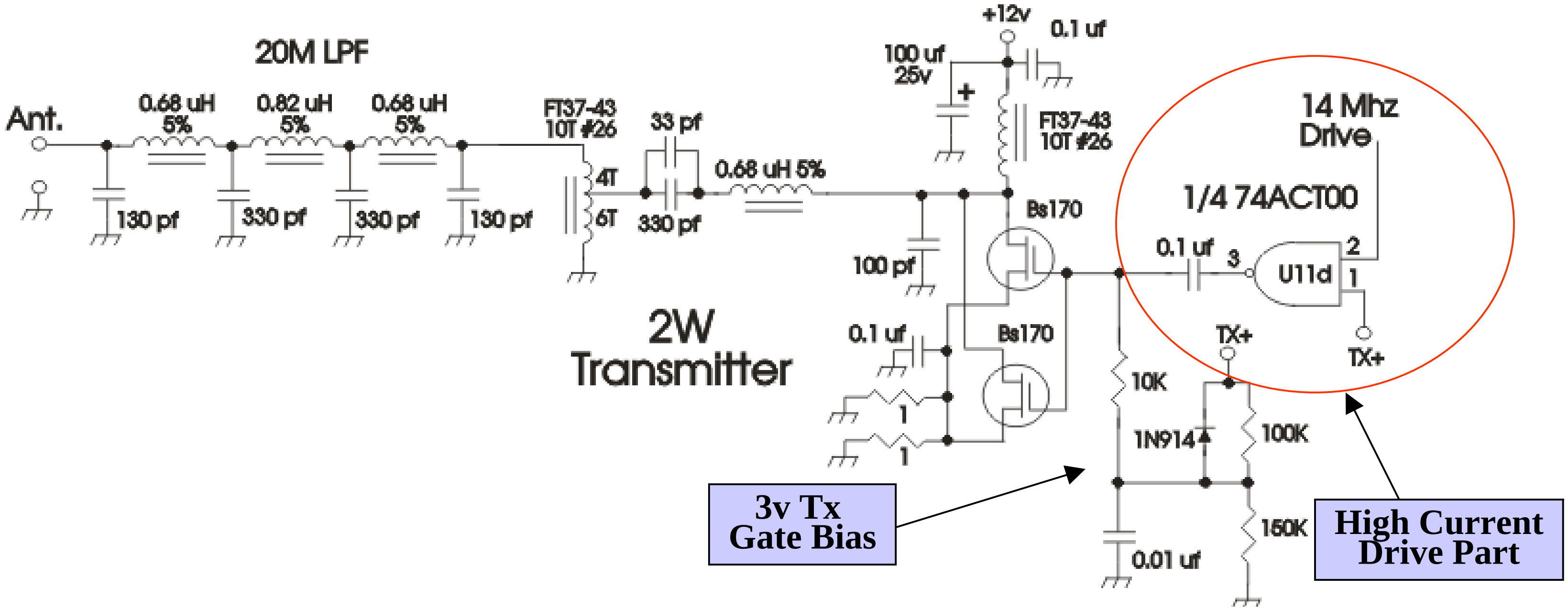
Solution: Use a broadband matching transformer!



- ***Broadband Transformer matches 20 ohm PA output to 50 ohm LPF***
- ***Transformer converts Class E reactive impedance without being frequency selective***
- ***However, efficiency is lower (~60%) as measured on 20 & 30m***

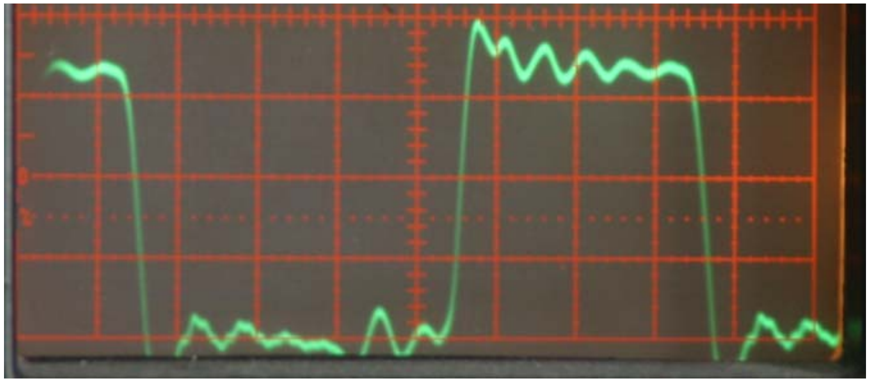
Class E Load Instability

Solution: Use a lower impedance gate driver!



- ***AC family has 24 ma of drive vs 8 ma for HC family***
- ***Higher current drive = lower drive source impedance***
- ***3x lower source impedance reduces tendency to "flight" with mismatched load***
- ***PA gate biased on TX to 3v to help MOSFET turn on harder***

Class E Driver – 74ACT00

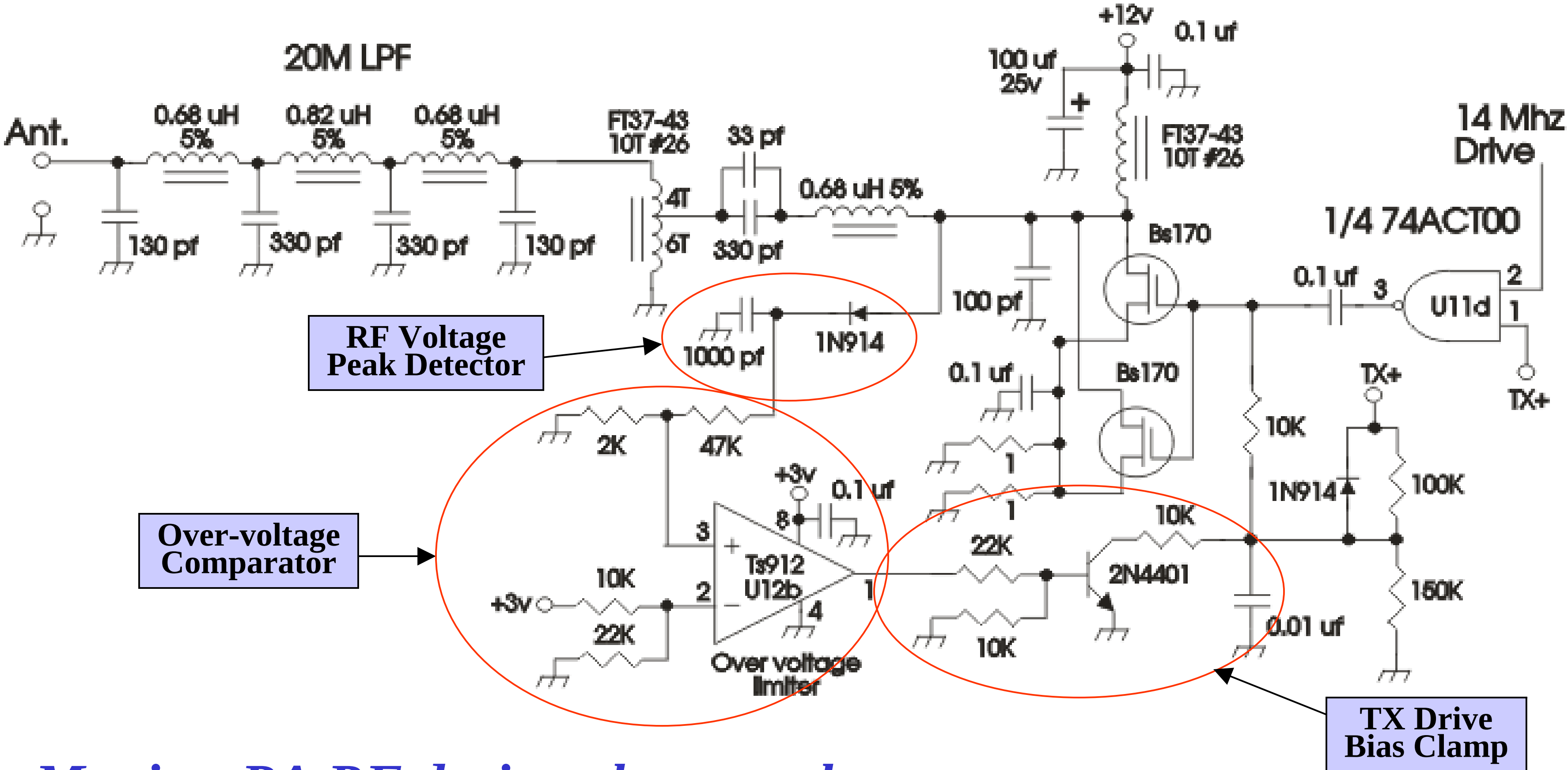


Scale: Vertical 2v/div, Horizontal 20 nsec/div
6 to 8v at peaks
Very fast rise+fall times: ~10 nsec total

74ACT00 has 24 ma of drive vs. only 8 ma for the more common 74HCT00 parts

Class E Voltage Limitations

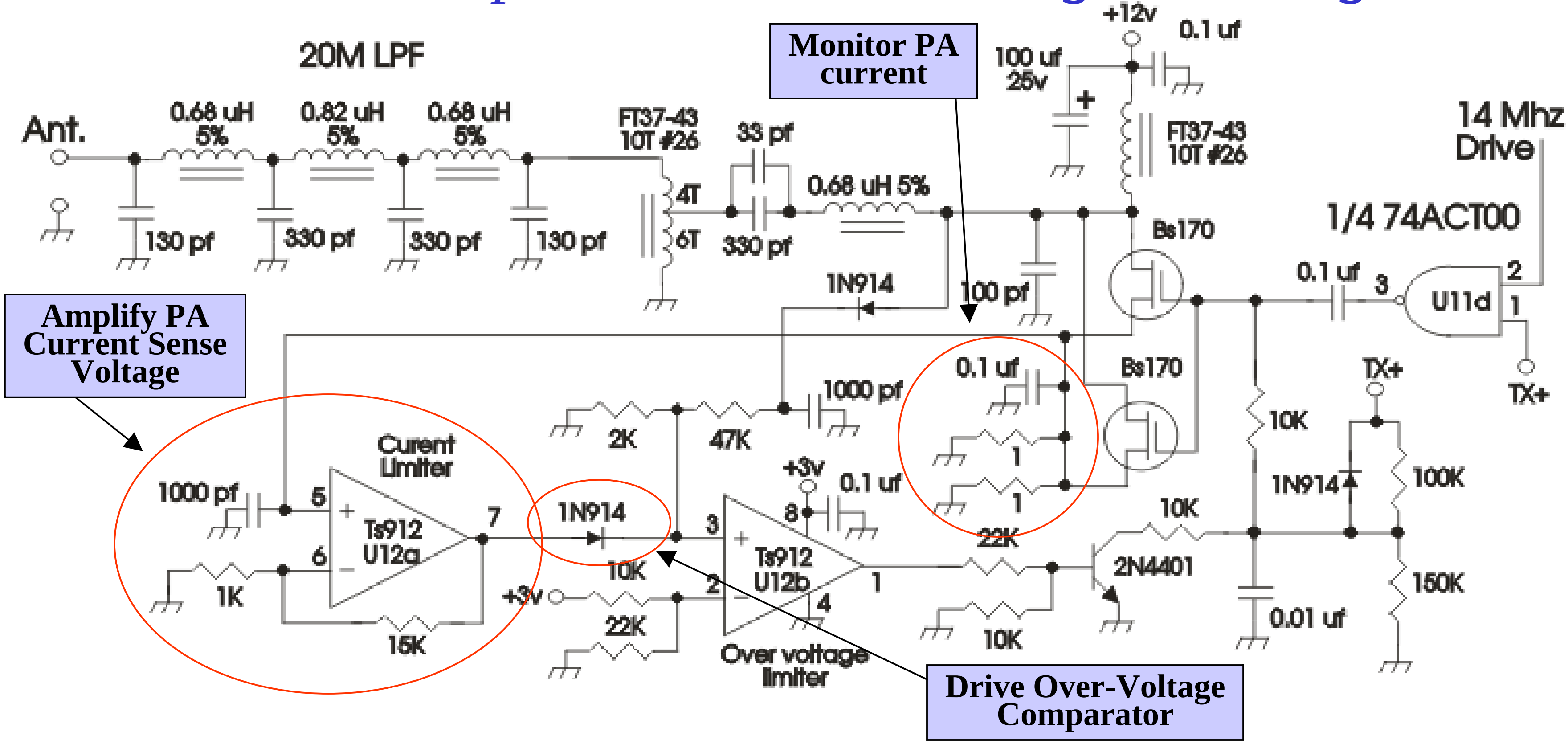
Reduce output when drain voltage gets too high!



- ***Monitor PA RF drain voltage peaks***
- ***If voltage gets higher than 55v, comparator triggers bias clamp***
- ***Reducing TX gate bias voltage reduces output power to safe limits***

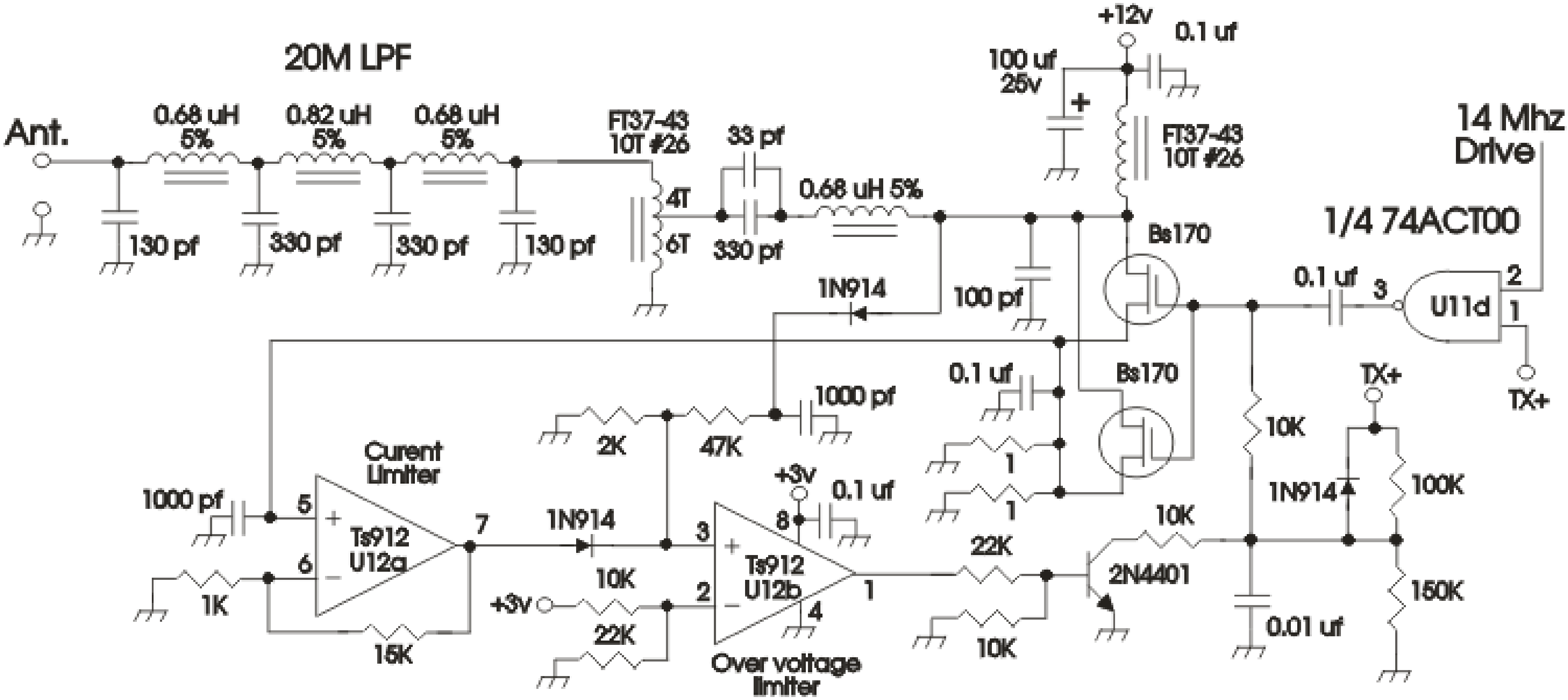
Class E Low Load Limitations

Reduce output when PA current gets too high!



- ***Use resistor voltage drop to sense PA current (~0.175v @ 0.35A)***
- ***Amplify sense resistor voltage by 15x (~2.6v max)***
- ***Use amplified voltage (less 0.6v) to trigger over-voltage circuit***
- ***Trigger reduces PA gate bias & TX output power, limits PA current***

No Tune, Goof Proof, Class E Tx



- ***High impedance over-voltage protection***
- ***Low impedance over-current protection***
- ***"No Tune" Class E output***

Current Class E Limitations

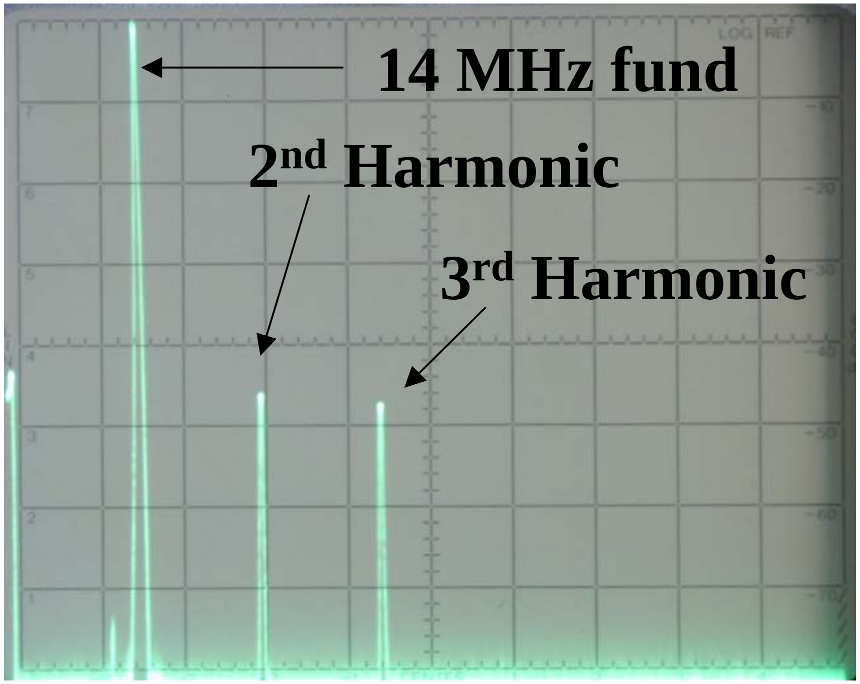
- Efficiency of common QRP PA devices (2N7000, BS170) drops off at ***14 MHz and above***
  - ***~80 to 90%*** efficiency at 10 MHz and below
  - ***~70%*** efficiency at 14 MHz
  - ~60 % efficiency using "no tune" approach shown here
  - R/C freq response: Smaller Driver R = Higher Freq response
    - ***Higher PA drive power can be used to get higher freq PA response***
    - ***Higher PA drive power hurts overall transmitter power saving***

- Higher frequency devices available, but more expensive
  - ***Example: STMicroelectronics PD57006s 900 MHz 5w FET, ~$12***

Current Class E Limitations, cont

- Class E operates at a ***fixed power*** set by Class E output network
- Variable power best done by changing supply voltage
- May be able to reduce power from preset maximum by lowering TX gate drive bias, but at reduced TX efficiency.

Transmitter Spectrum



Scale 10 db/division – legal limit 30 db down

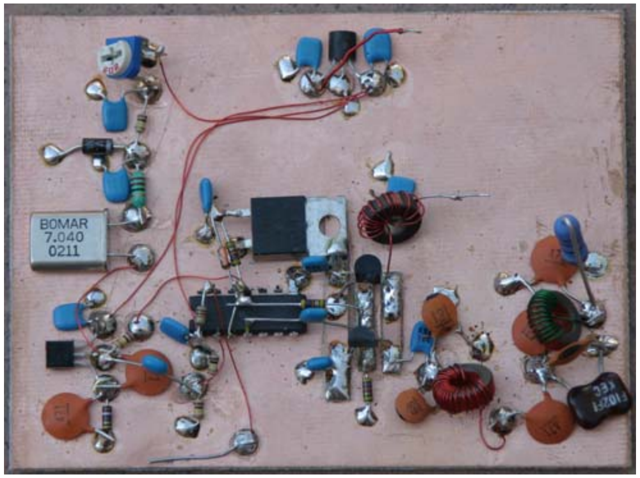
2nd Harmonic *~45 db* down

3rd Harmonic *~47 db* down

All other more than 70 db down

Class E Amplifiers

Part 3: Good & Bad QRP Class E Devices
Or
"Bigger is not Better"



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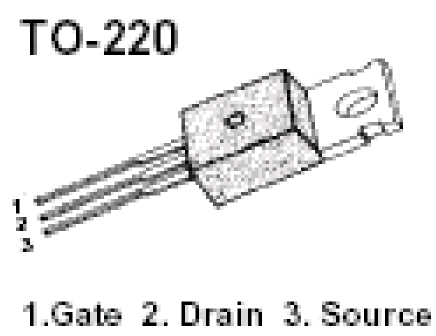
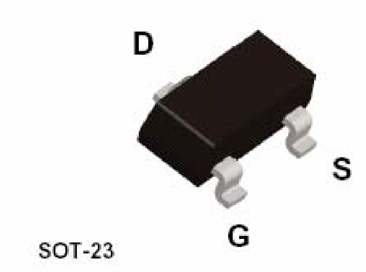
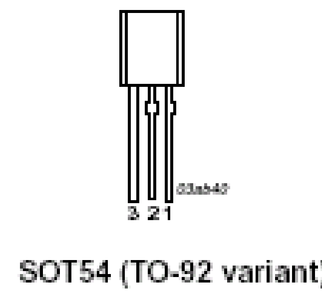
Why the IRF510 Makes a Good 5w ***Class C*** PA

- IRF510 on/off time 70 nsec, good to 14 MHz
- 40 to 45% efficiency typical using broadband, low pass TX output filters
- **5w** output requires **11.1w** input power
  - ***6.1w of heat produced!***
  - ***33w IRF510 can take the heat if proper heat sink is used***

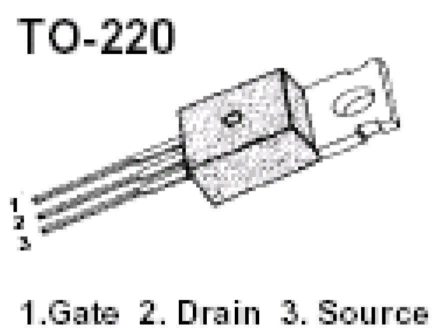


Why the 2N7000 makes a good QRP ***Class E*** final





and the IRF510 *does not*



Good FET – 2N7000, 0.3 to 0.6w

Dynamic characteristics						
g_{fs}	forward transconductance	V_{DS} = 10 V; I_D = 200 mA; Figure 11	100	300	–	mS
C_{iss}	input capacitance	V_{GS} = 0 V; V_{DS} = 10 V; f = 1 MHz; Figure 12	–	25	40	pF
C_{oss}	output capacitance		–	18	30	pF
C_{rss}	reverse transfer capacitance		–	7.5	10	pF
t_{on}	turn-on time	V_{DD} = 50 V; R_D = 250 Ω; V_{GS} = 10 V; R_G = 50 Ω; R_{GS} = 50 Ω	–	3	10	ns
t_{off}	turn-off time		–	12	15	ns

Low input C: 25 pf typical – Low input drive drive!

Fast Turn on/off time: 3+12 nsec = *15* nsec

For class E, need On/Off to be 30% of ½ RF cycle (QEX 1/01)

- Gives maximum limit of 10 MHz for full efficiency
- Can be used at 14 MHz at reduced efficiency
    - *Measured 80-90% at 7 & 10 MHz, 70% at 14 MHz*

Difficult FET – IRF510, 33w

C_{iss}	Input Capacitance	--	190	240	pF	V_{GS}=0V, V_{DS}=25V, f = 1MHz **See Fig 5**
C_{oss}	Output Capacitance	--	55	65		
C_{rss}	Reverse Transfer Capacitance	--	21	25		
$t_{d(on)}$	Turn-On Delay Time	--	10	30	ns	V_{DD}=50V, I_D=5.6A, R_G=24Ω **See Fig 13** (4)(5)
t_r	Rise Time	--	14	40		
$t_{d(off)}$	Turn-Off Delay Time	--	28	70		
t_f	Fall Time	--	18	50		

Higher input C: 190 pf typical – Higher input drive needed!

- *Specs use 24 ohm source here vs. 50 ohm source for 2N7000*

Slower Turn on/off time: 10+14+28+18 nsec = *70* nsec

For class E, need On/Off to be 30% of ½ RF cycle

- Gives maximum limit of 2 MHz for full efficiency
- Can speed up by using a lower impedance drive source.
  - *Slam it on, slam it off! – more drive power needed.*

Double driver power hit: High input C & Slow switching time

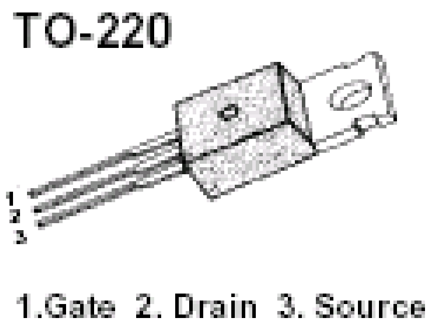
Class E Driver Requirements IRF510 vs. 2N7000

- IRF510, 190 pf input gate C; 2N7000, 25 pf
  - Drive power factor of 7.6x
- IRF510, 25 ohm source; 2n7000, 50 ohm source
  - Drive power factor of 2x
- IRF510, 70 nsec turn on/off; 2n7000, 15 nsec
  - Need 4.67x lower drive impedance to get same speed
    - IRF510 requires ***5 ohm*** driver impedance for 15 nsec on/off

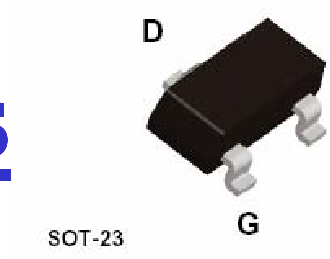
Total drive difference: IRF510 needs 71x more drive power than a single 2N7000

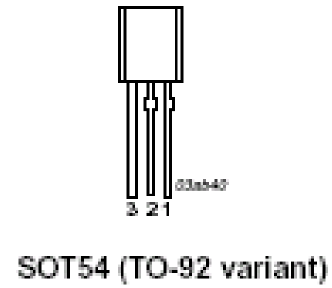
- ***~ 0.6w drive for class E IRF511 vs. 17mW for a pair of 2N7000s***

IRF510: Good 100w Class E amp, poor 5w amp!



Conclusions





- ***Class E* saves ~ 50% on TX DC input power to PA**
  - ***Low drive power (17 mW vs. 0.6w) saves additional power***
- Class C requires large TO220 PA transistors
- Class E needs only tiny T092/SOT23 300mw/600mw packages
- $0.14 for a new pair of Class E QRP finals!
- Low wasted TX pwr (*Heat*)
  - *For 5w output, 0.5 to 1w heat (class E) vs. 5 to 6w heat!*
  - Conserves battery life (smaller battery?)
  - Reduces VFO drift

Class E Summary

- ***Class E can give up to 88% efficiency***
  - But require tuning to get proper power output
- ***Protection circuitry available for Class E finals***
  - Protects against antenna open/short/mismatch problems
- ***"No Tune" Class E works, but ~60% efficiently***
- ***Bigger is not better for Class E finals***
  - High power MOSFETs (such as the IRF511) require high drive power (*71x!*), reducing overall rig efficiency.

