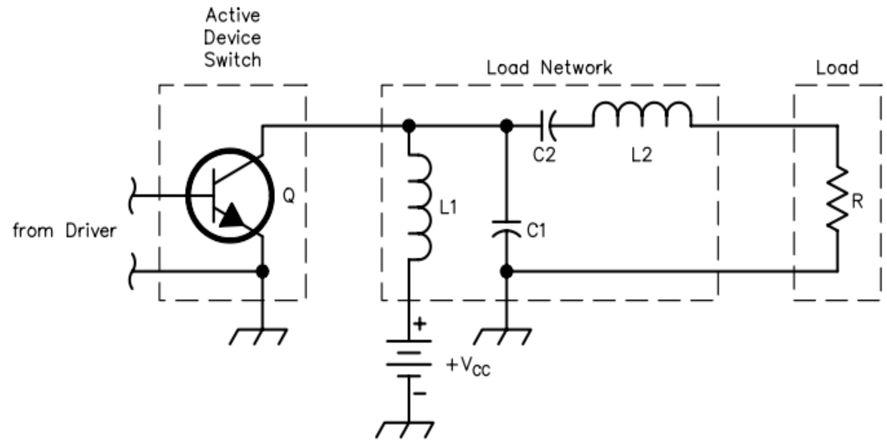


Designing, Building and Pitfalls of simple Class-E transmitters

A beginner's guide by a beginner experimenter

Dimitris Tsifakis VK1SV

Overview

- Introduction to Class-E
- Design and implementation of a Class-E amplifier
- Selecting a FET
- Other component selection
- Good and not so good waveforms
- Special topics
- Ideas

Introduction to Class-E

- Class A (360°), B(180°) and C(120°)
- Class D: Switching amplifier
- Class E: Read the Sokal article!
  - General concept is high voltage and high current do not exist at the same time across the switching device (FET)
  - High efficiency (typically much better than 80%)
  - Easy to design, works every time!
  - Suitable for single FET transmitters

Examples of Class-E transmitters

Table 2—Example Class-E Power Amplifiers

Frequency	Power	Transistor	Collector or Drain Efficiency/PAE	Organization	Approximate Year	See Reference
0.52-1.7 MHz	44 kW PEP	push-pull MOSFETs	95%	Broadcast Electronics, Inc	1992	34
14 MHz	110 W	International Rectifier IRF540	92%	Design Automation, Inc	1986	36
13.56 MHz, 27.12 MHz	2 kW	MOSFET	90%	Dressler Hochfrequenztechnik	1993	
13.56 MHz	3 kW, 5.5 kW	MOSFET	?%	Advanced Energy Industries, Inc	1992-1997	
27.12 MHz	22 W	International Rectifier IRF510	89-92%	Design Automation, Inc	1991	37
145 MHz	2.58 W	Siliconix VMP4 VMOSFET	96.5%/81.3%*	École Polytech. Féd. Lausanne	1980	32
300 MHz	30 W	push-pull BJTs	89%	Harris RF Communications	1992	39
450 MHz	14.96 W	combine 4 modules MRF873 BJT	89.5%	City Univ. of Hong Kong	1997	30
500 MHz	0.55 W	Siemens CLY5 GaAs MESFET	83%/80%	Univ. of Colorado	1995	23
840 MHz	1.24 W	GaAs MESFET	79%/77%	S. C. Cripps	<1999	40
850 MHz	1.6 W	GaAs MMIC	62.3% PAE	M/A-COM	1994	26
1 GHz	0.94 W	Siemens CLY5 GaAs MESFET	75%/73%	Univ. of Colorado	1995	22, 21
2.45 GHz	1.27 W	Fujitsu FLC30 GaAs MESFET	72% PAE	RCA David Sarnoff Res. Ctr.	1981	13
2.45 GHz†	210 mW	Raytheon RPC3315 MESFET	77%/68%/71%*	Design Automation, Inc	1979	33
5 GHz	0.61 W	Fujitsu FLK052WG MESFET	81%/72%	Univ. of Colorado	1996	12, 23
8.35 GHz	1.41 W	Fujitsu FLK202MH-14 MESFET	64%/48%	Univ. of Colorado	1999	41
10 GHz	100 mW	Alpha Ind. AFM04P2 MESFET	74%/62%	Univ. of Colorado	1999	42

*Overall efficiency = $P_{out}/(P_{dc} + P_{drive})$

†1/20 scaled-frequency model at 122.5 MHz; see Reference 33.

Requirements

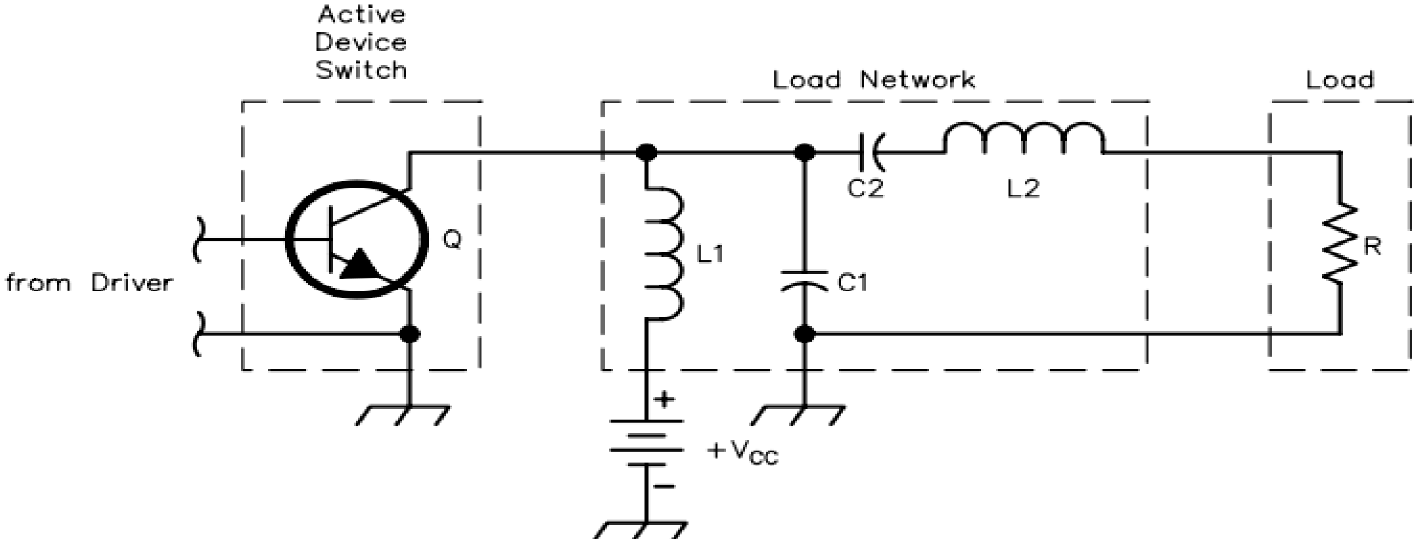
- A plan with a clear target (P_{out}, V_{cc}, etc)
- Driving circuit (depends)
- A FET (common: Jaycar/eBay/RS/etc)
- Suitable Capacitors (eBay/Junkbox/Jaycar?)
- Suitable inductors (eBay/RS/Junkbox/etc)
- Fingers!
  - For testing which component gets hot!
- Oscilloscope and DMM
  - Waveforms help with troubleshooting
- Dummy load

Class-E RF Power Amplifiers

Come learn about this highly efficient and widespread class of amplifiers. Here are principles of operation, improved design equations, optimization principles and experimental results.

By Nathan O. Sokal, WA1HQC
of Design Automation, Inc
ARRL Technical Advisor

Sokal article (the important bits)



$$R = \left(\frac{(V_{CC} - V_o)^2}{P} \right) 0.576801 \left(1.0000086 - \frac{0.414395}{Q_L} - \frac{0.577501}{Q_L^{\,2}} + \frac{0.205967}{Q_L^{\,3}} \right)$$

$$C1 = \frac{1}{34.2219\, f\, R} \left(0.99866 + \frac{0.91424}{Q_L} - \frac{1.03175}{Q_L^{\,2}} \right) + \frac{0.6}{(2\pi\, f)^2\, L1}$$

$$C2 = \frac{1}{2\pi\, f\, R} \left(\frac{1}{Q_L - 0.104823} \right) \left(1.00121 + \frac{1.01468}{Q_L - 1.7879} \right) - \frac{0.2}{(2\pi f)^2\, L1}$$

$$L2 = \frac{Q_L\, R}{2\pi\, f}$$

Design

- Sokal article
- VK2ZAY online calculator
- Alan Melia G3NYK spreadsheet
  - http://www.alan.melia.btinternet.co.uk/classepa.htm
- Driving circuit
  - Square wave, ~50% duty cycle, drive FET to saturation (8 or 9 volts, depends on FET)
  - MOSFET drivers
  - CMOS – TTL -DDS – Signal generator
  - The capacitive reactance of C_{iss} will determine the driving requirements

Driving the FET

- Ferrite bead on gate pin or a few ohms in series to avoid parasitic VHF oscillations
- Driving a capacitor (Ciss)
- Xc=1/2*pi*f*C
- For low C, F drive directly from CMOS IC?
- Dedicated MOSFET driver ICs
  - TC4420, TC4427, etc
- A FET to drive the FET?

Design: common FETs

FET	V_{ds}(I)	$R_{ds(on)}$	C_{iss}	C_{oss}	Comments
2N7000	60 V (0.2A)	1.2 Ω	20 pF	11 pF	QRP, maybe up to 1 W
IRF510	100 V (5.6A)	0.54 Ω	135 pF	80 pF	Common 5 W to 10 W QRP FET
IRF520	100 V (9.2A)	0.27 Ω	360 pF	150 pF	Around 20 W max?
IRF540	100 V (28A)	0.077 Ω	1.7 nF	560 pF	100 W from 12 V?
IRF640	200 V (18A)	0.18 Ω	1.3 nF	430 pF	200 W from 24 V?
IRF840	500 V (8A)	0.85 Ω	1.2 nF	200 pF	For high voltage (100 V?) designs

Always check the correct datasheet for your component!

Design: calculations

Class-E RF Amplifier

Based on the Nathan Sokal WA1HQC equations.

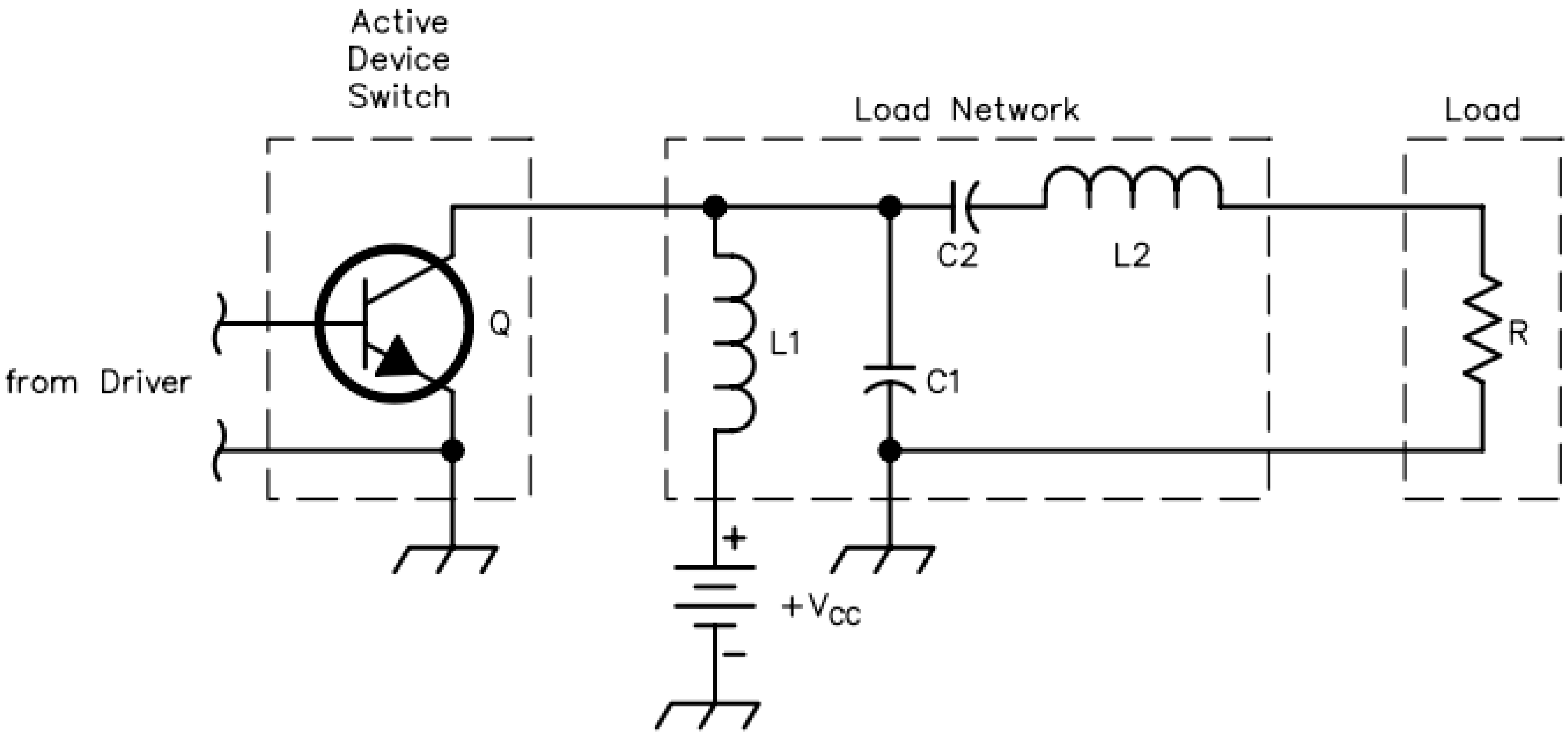
Power Output	25	Watts
Supply Voltage	12.5	Volts
Saturation Voltage	0.2	Volts
Loaded Q	5	1.79-∞
Frequency	137777	Hertz
Feed Choke	0.00047	Henries

calculate

Load Resistance	3.126 Ω
C1	79.055 nF
C2	98.846 nF
L2	18.058 uH

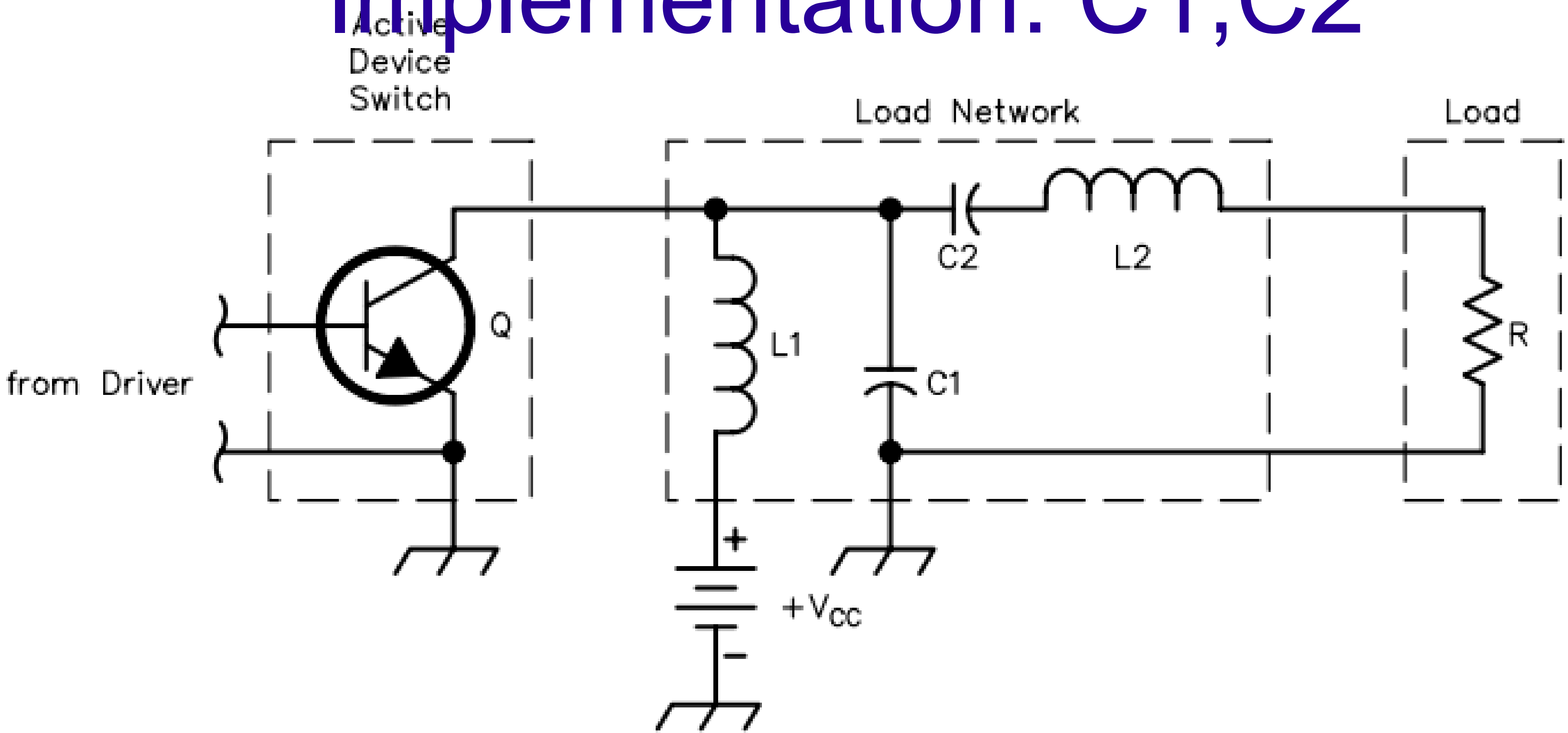
- VK2ZAY online Class-E calculator
  - **Experiment with it!**
- Feed Choke = L1
- Saturation Voltage is I * $R_{ds(on)}$
- 5 is a good starting value for Loaded Q
- Supply voltage should not be more than $(V_{ds}/3.56)*SF$
  - SF: safety factor, 0.8 or 0.9 or so...

Implementation: L1



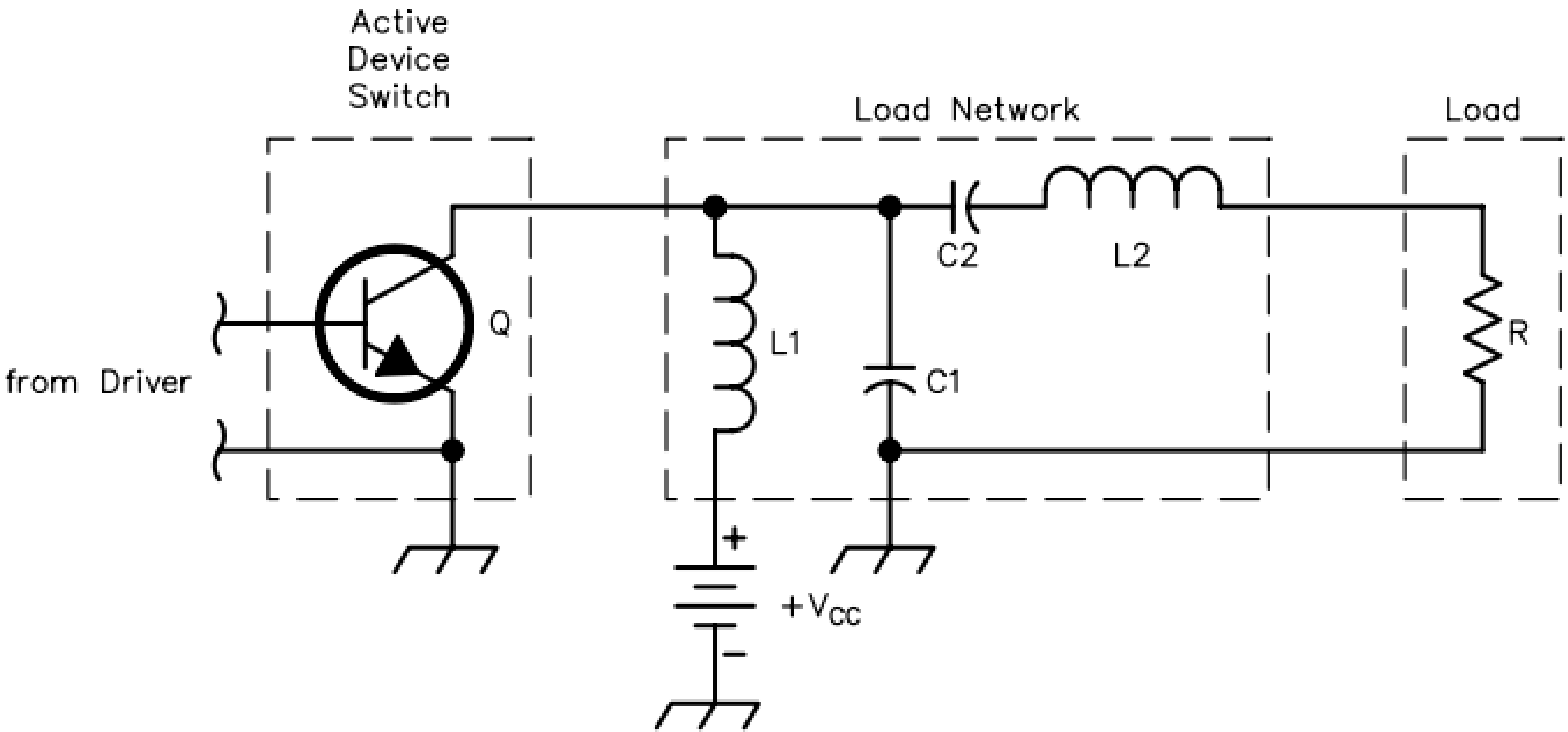
- Not critical!
- 30x the load impedance
- Ferrite toroid

Implementation: C1,C2



- C1 = C_{oss} + Extra capacitance
- High current capacitors, WIMA FKP/MKP or Silver-mica
- HV ceramic may be OK but beware of losses and temperature coefficient

Implementation: L2



- Amidon mix 2 for LF to 40m, mix 6 for higher frequencies
- Critical

Implementation: impedance transformer

- Primary: 3x or more the load impedance
  - X_L=2*pi*f*L
- Secondary according to formula:
  - N1/N2=SQRT(Z1/Z2)
- Ferrite
  - High AL RFI ferrites seem to work OK
  - Experiment
- Finger test for efficiency!

Waveforms

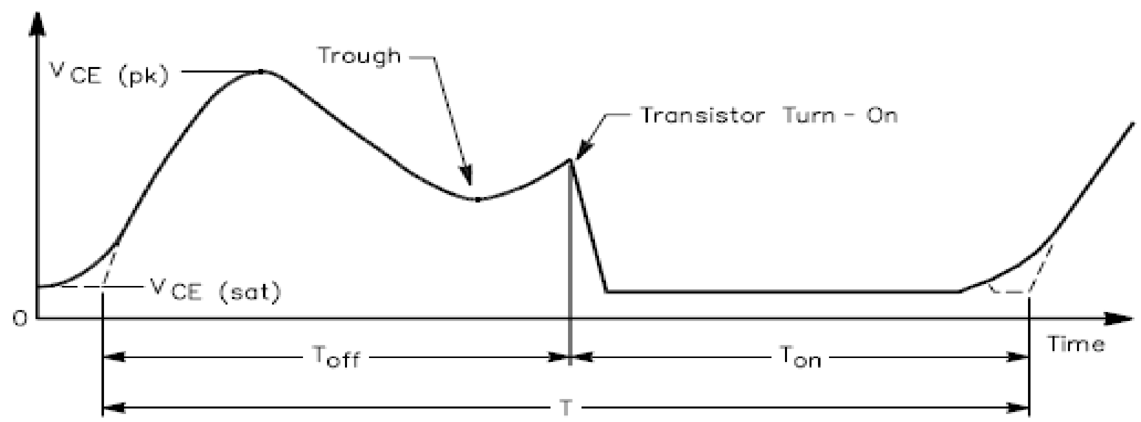


Fig 4—Typical mistuned V_{CE} waveform, showing transistor turn-on, turn-off and waveform "trough."

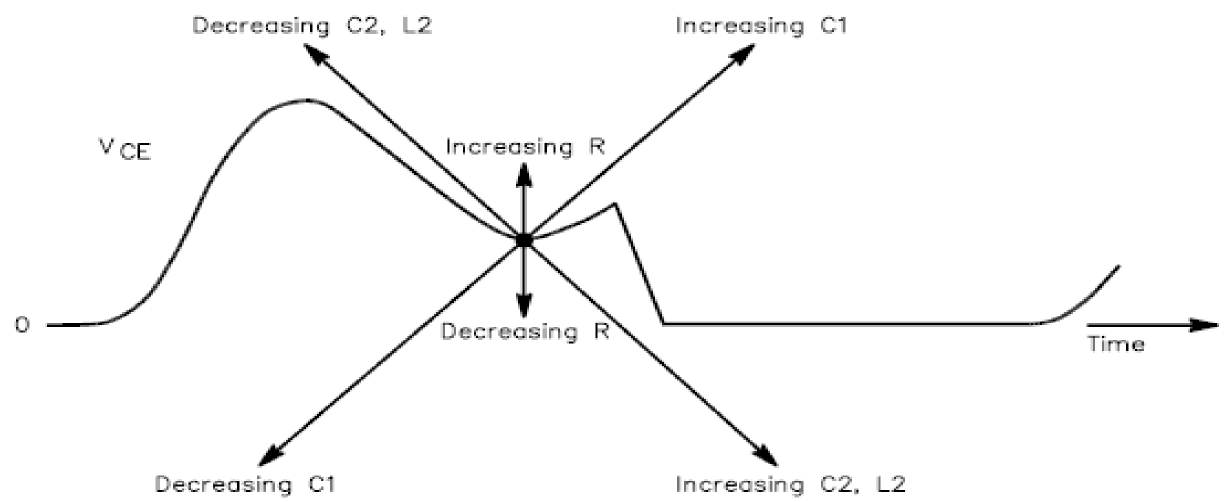
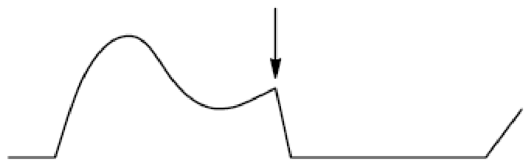
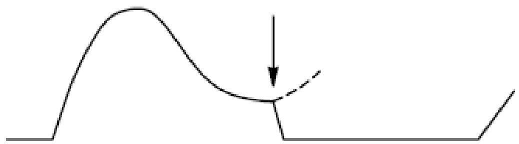
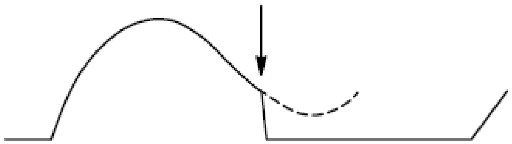
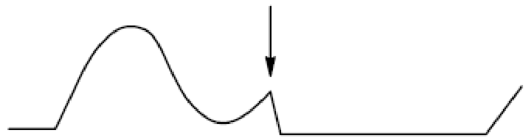
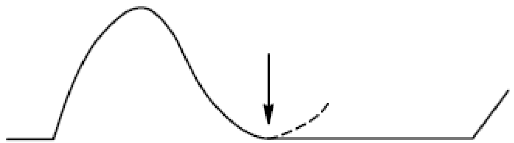
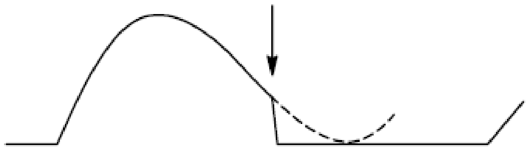
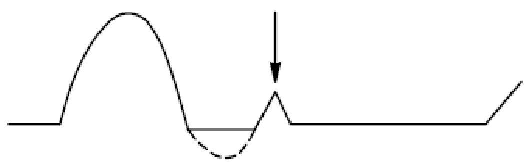
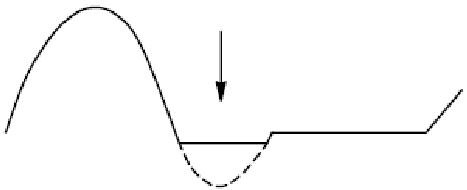
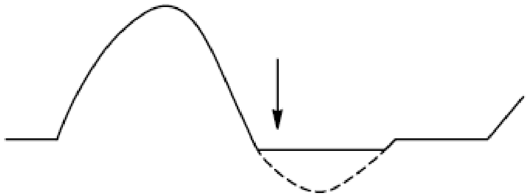
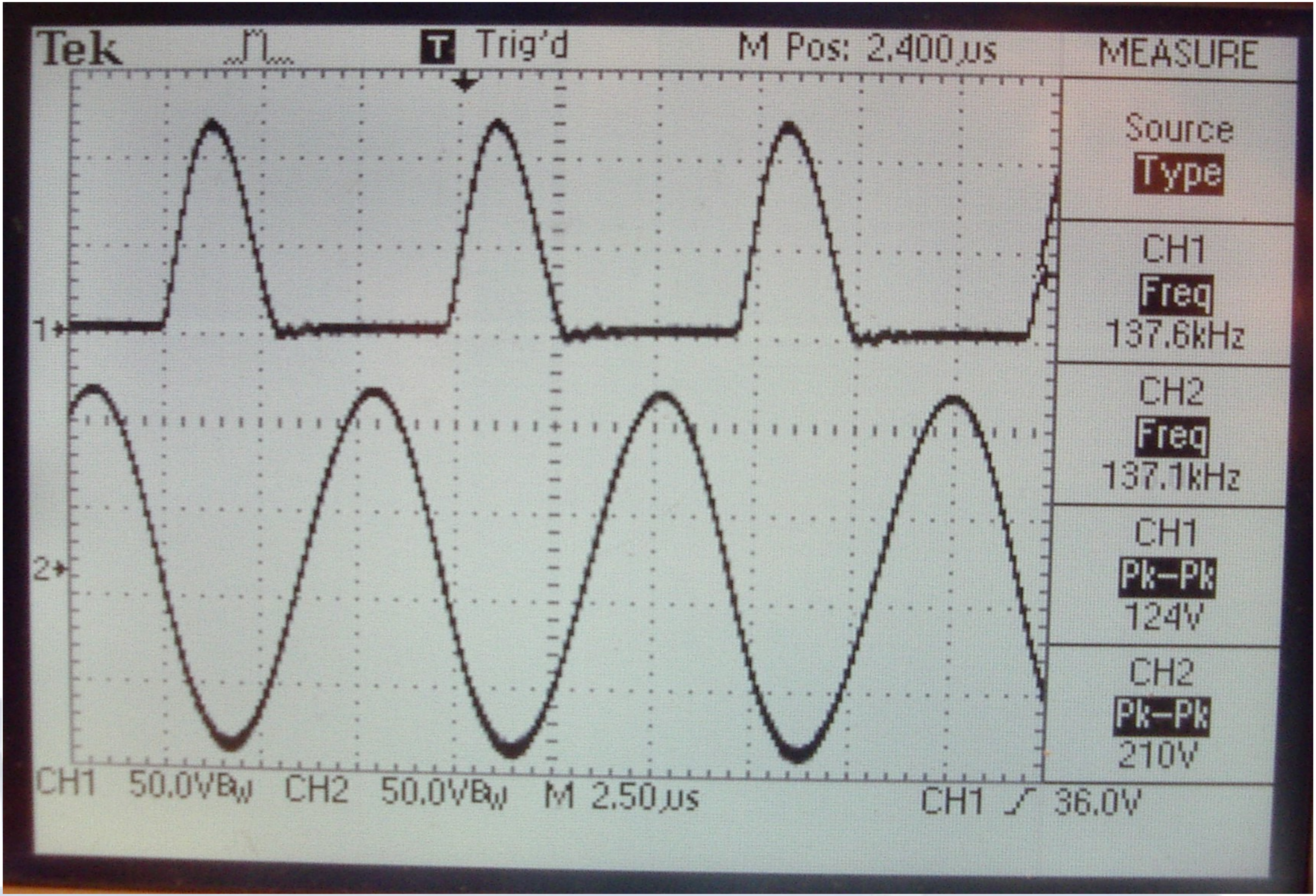


Fig 5—Effects of adjusting load-network components.

More waveforms

V_{CE} Relative to $V_{CE(sat)}$ at Time of Zero Slope	V_{CE} Slope at Transistor Turn On: Positive; Increase (C1 Series C2)	Zero; Keep Same (C1 Series C2)	Negative; Decrease (C1 Series C2)
More Positive; Decrease C1/C2	 Increase C2	 Decrease C1 and Increase C2	 Decrease C1
Equal; Keep Same C1/C2	 Increase C1 and C2 in same Proportion	Nominal Calss E Waveform  Finished Adjusting C1 and C2. Go to Step 7	 Decrease C1 and C2 in Same Proportion
More Negative; Increase C1/C2	 Increase C1	 Increase C1 and Decrease C2	 Decrease C2

Result: waveforms



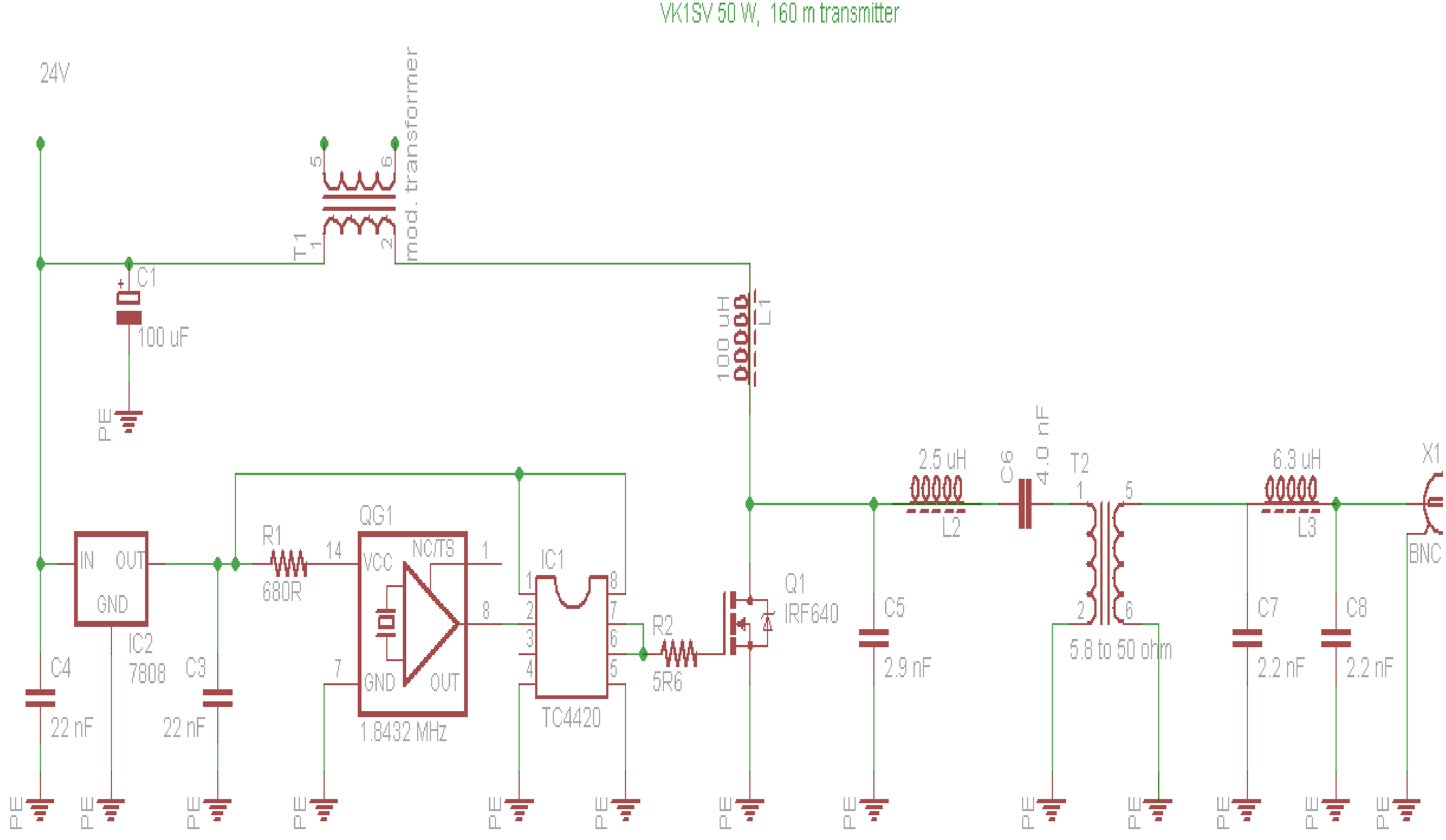
Finishing touch, hints and tips

- Harmonics are -20 dBc or better
- An LPF is needed (but it's not going to work very hard!)
  - WA4DSY web site
  - SM caps and -2 or -6 mix
- Heat sink on FET
- Toroid calculator
  - http://toroid.info/T50-2

Special topics: Amplitude modulation

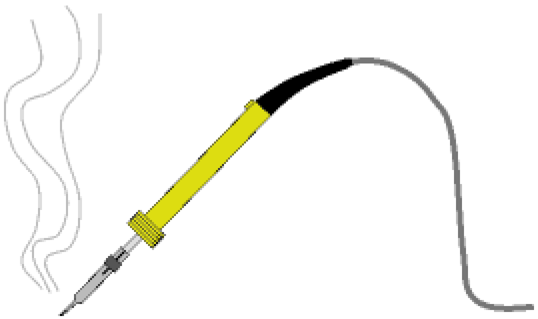
- Easiest option: drain modulation
  - Voltage should swing between 0 V and 2x V_{cc} for 100% modulation
  - Design for 2x V_{cc}, ensure FET and other components are suitable for that power
  - Modulation transformer: dare I suggest a big power toroid with appropriate turns ratio?
- Other maybe interesting option: modulation by duty cycle change of the gate driving signal
  - Homework for high achieving students!
  - (I have not tried this, but I think it's a valid way of doing this)

AM example


VK1SV 50 W, 160 m transmitter
24V
T1
mod. transformer
C1
100 uF
L1
100 uH
PE
R1
680R
QG1
VCC
NC/TS
GND
OUT
1.8432 MHz
IN
OUT
GND
IC2
7808
C4
22 nF
C3
22 nF
IC1
TC4420
R2
5R6
Q1
IRF640
2.5 uH
L2
C6
4.0 nF
T2
5.8 to 50 ohm
C5
2.9 nF
6.3 uH
L3
C7
2.2 nF
C8
2.2 nF
X1
BNC

Ideas

- LF/MF transmitter of course!
- 10.140 MHz QRSS beacon (other freqs too!)
- AM transmitter for 160m/80m/40m
  - 7.125 MHz AM hobebrewer's network every Saturday morning
  - Combine with super simple single conversion superhet receiver,based on AM-radio-in-a-chip (a topic for a future presentation?)
- High power CW transmitter that fits in your pocket
  - Watch those key clicks!
- QRP CW transmitter for field/fun use!
  - Xtal oscillator
- Dedicated WSPR beacon (combine with DDS)
- Opera beacon (like WSPR only single freq – CW TX)



Questions?