A Single-Transistor Class C Amplifier

50 Watts Output for 30m CW

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Introduction

- **QST, Mar. 1983**: Doug DeMaw publishes "Go Class B or C with Power MOSFETS" showing how inexpensive transistors can be used in RF power amplifiers

- **QST, Nov. 1989**: Wes Hayward and Jeff Damm publish "Stable HEXFET RF Power Amplifiers" showing examples of single-device CW amplifiers yielding up to 50W output on 20 meters

- Design here is motivated by previous results and is for 30 meters

- True **class C amplifiers** (devices off under quiescent conditions) are suitable only for CW operation

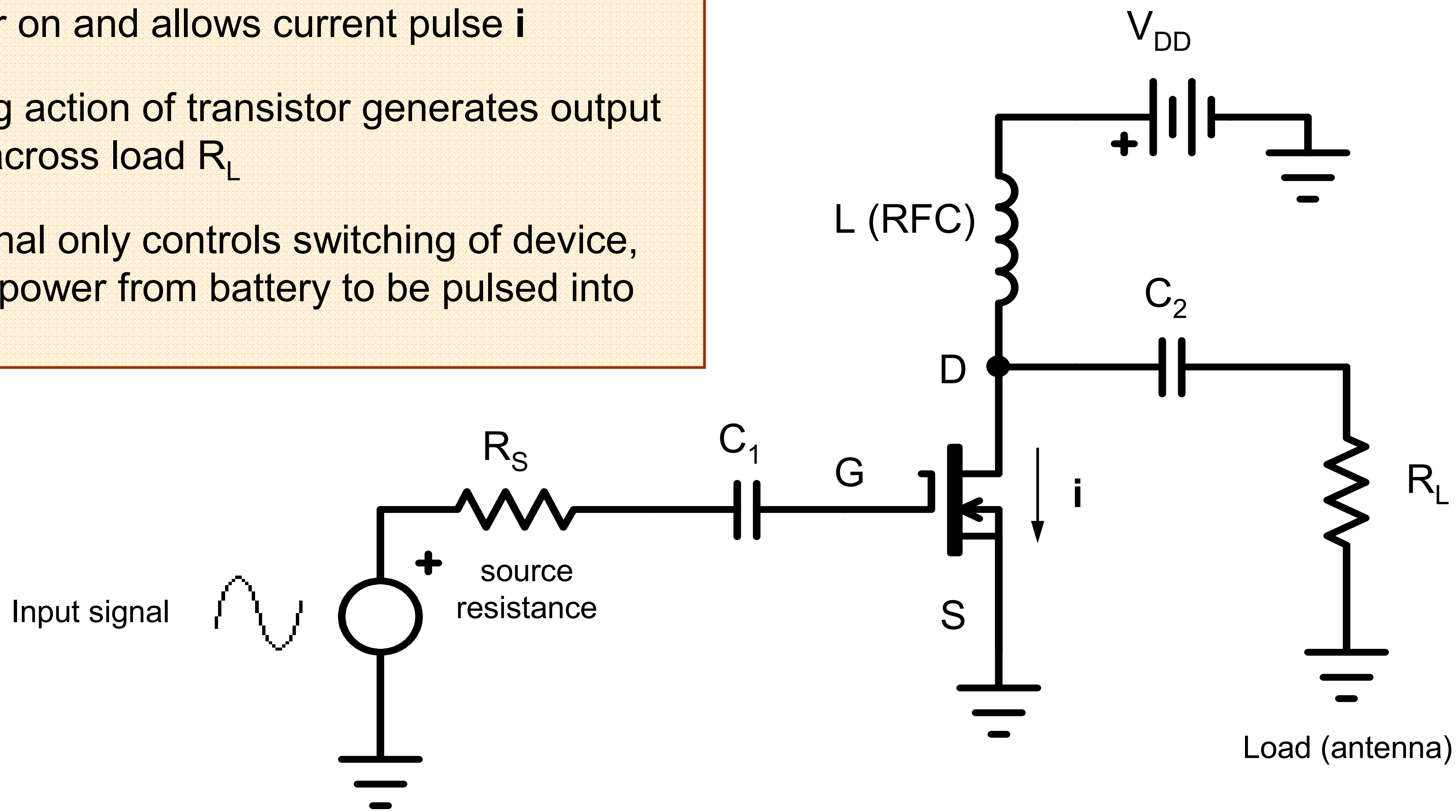
- Allowing device idling currents (devices on under quiescent conditions) is closer to **class A** operation and permits linear amplification for SSB

Outline

- Explanation of class C operation for an RF amplifier
- Design procedure for 50W, 30m amplifier with V_{DD}=24V and input power P_{in} of 5W.
  - *Note: Amplifier will work with lower V_{DD} and P_{in} providing lower output power.*
- Emphasis on physical understanding
- Demonstration of constructed circuit

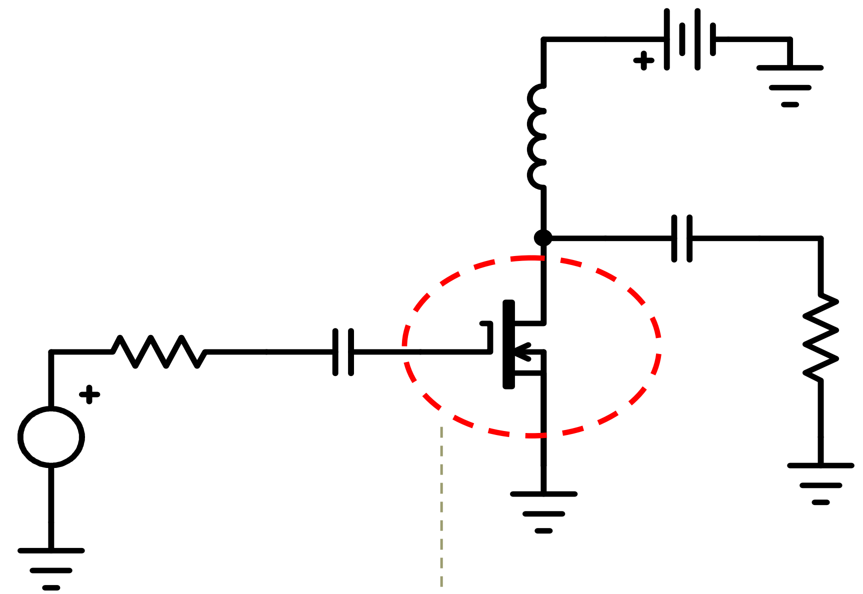
Basic Structure of a Class C Amplifier

- With no input signal, transistor is biased at cutoff (no current through device; i=0)
- Input signal of sufficient magnitude turns transistor on and allows current pulse **i**
- Switching action of transistor generates output voltage across load R_L
- Input signal only controls switching of device, allowing power from battery to be pulsed into the load



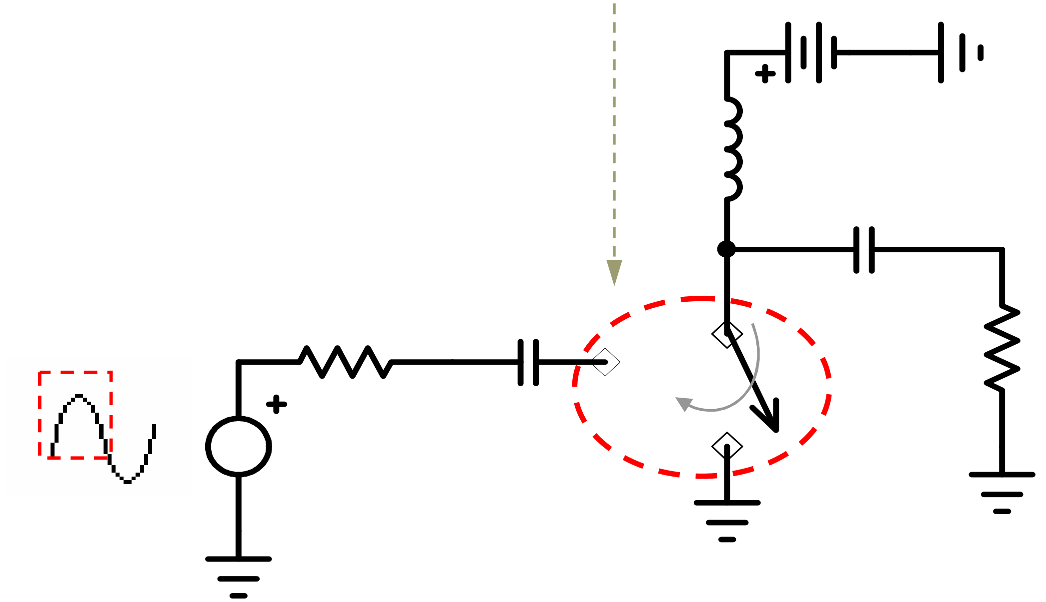
Ideal-Switch Model of a Class C Amplifier

Original circuit



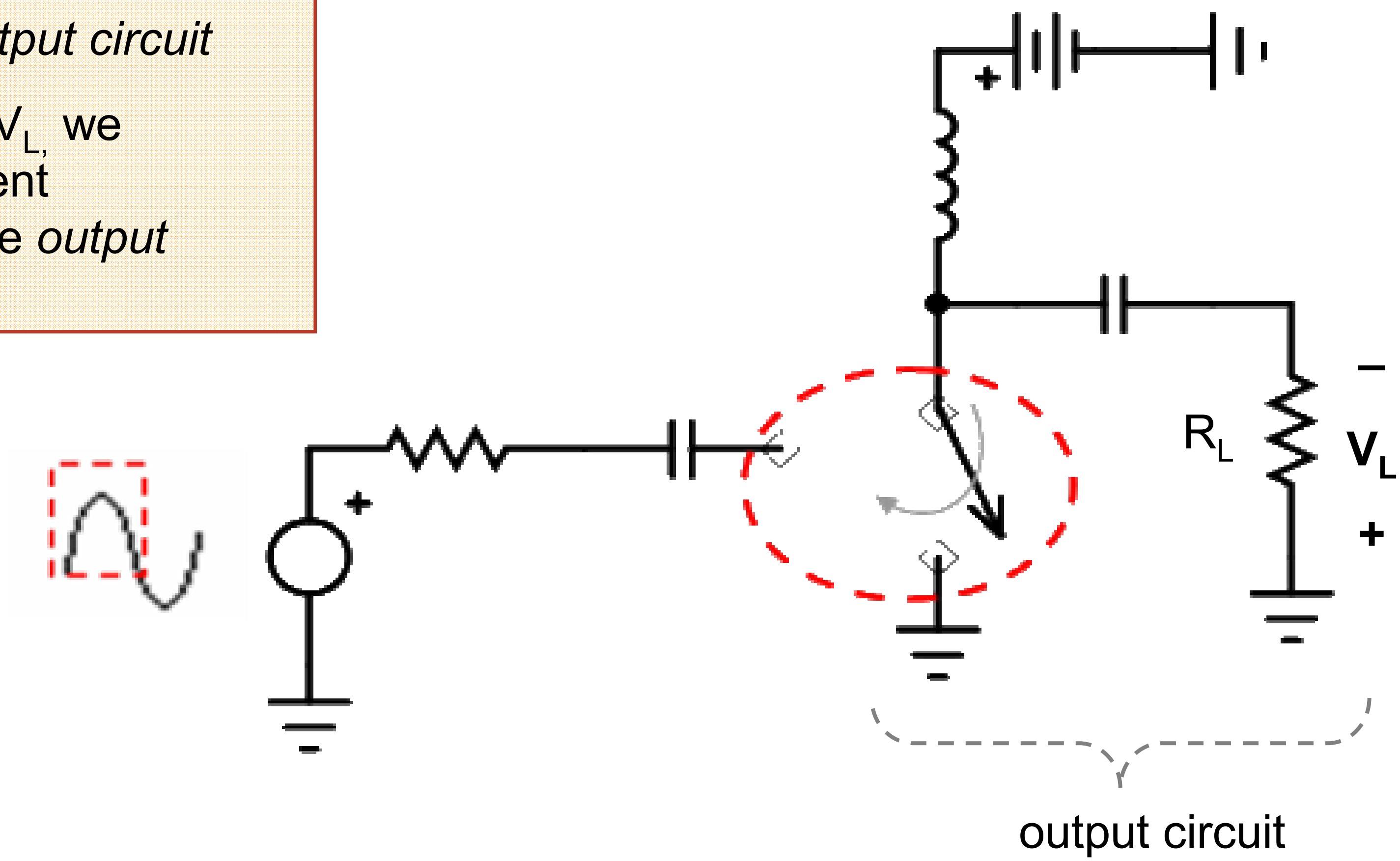
Ideal-switch model of transistor:

- switch shorts to ground when input signal is positive
- switch opens when signal is zero or negative



Analysis of Idealized Class C Amplifier – Output Voltage Waveform

- We seek the output voltage waveform $\mathbf{V_L}$ across R_L
- Positive-valued input signal closes switch
- We examine the *output circuit*
- For ease in finding V_L, we develop an equivalent representation of the *output circuit*



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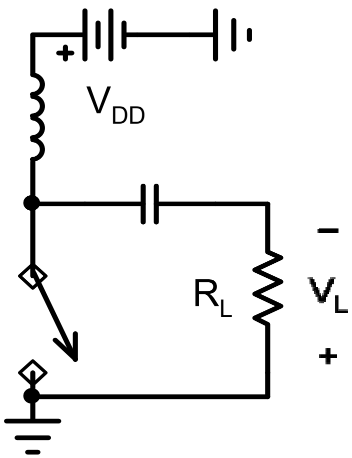
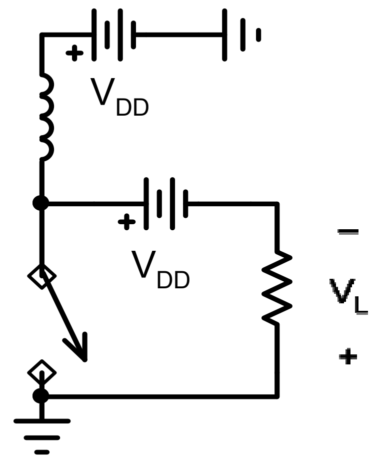
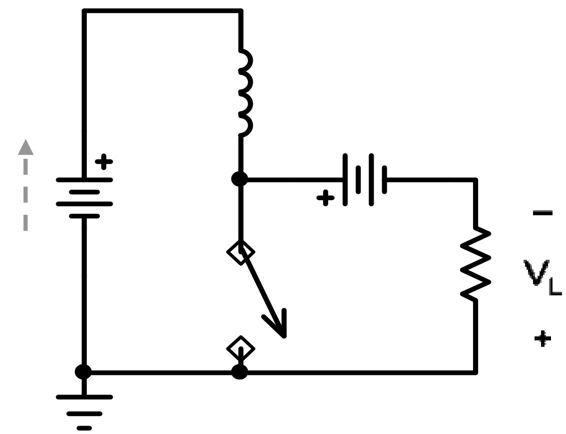


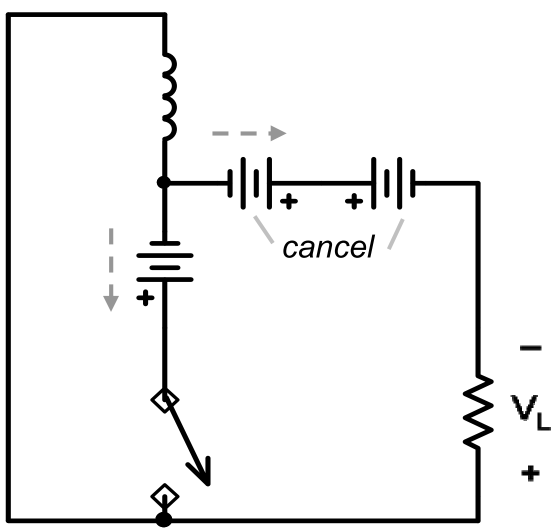
Output circuit



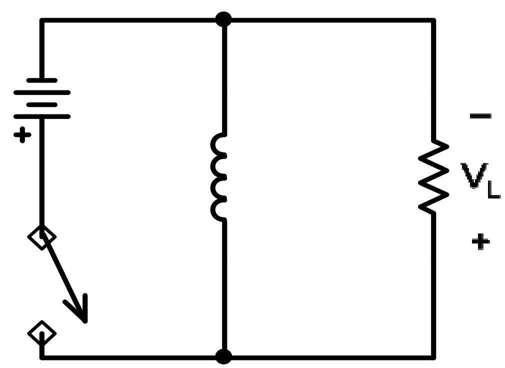
Replacing C_2 with another V_{DD}



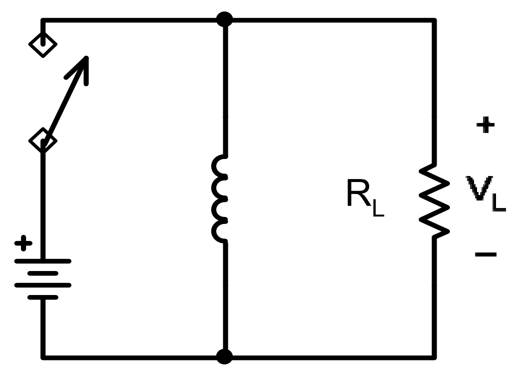
Simple redrawing of circuit



Voltage push-through theorem



Redraw



Redraw again

Output Voltage Waveform of Idealized Class C Amplifier - 1

For t<0, input signal is at zero and switch is open

At t=0, input signal goes positive and switch closes. V_L immediately jumps to $+V_{DD.}$ The inductor current i_L quickly but continuously rises from zero to a positive value over $0<t<t_1$

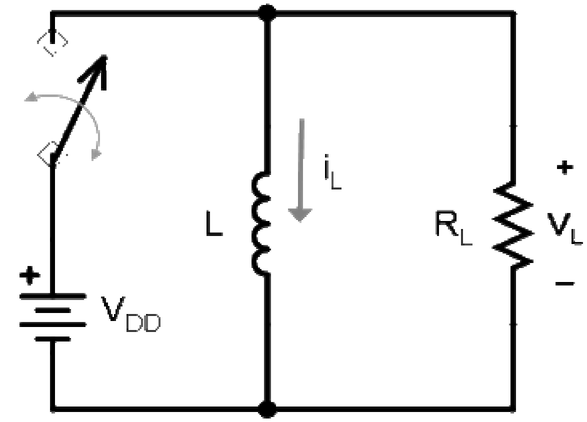
At t=t₁ input signal drops to zero and the switch opens

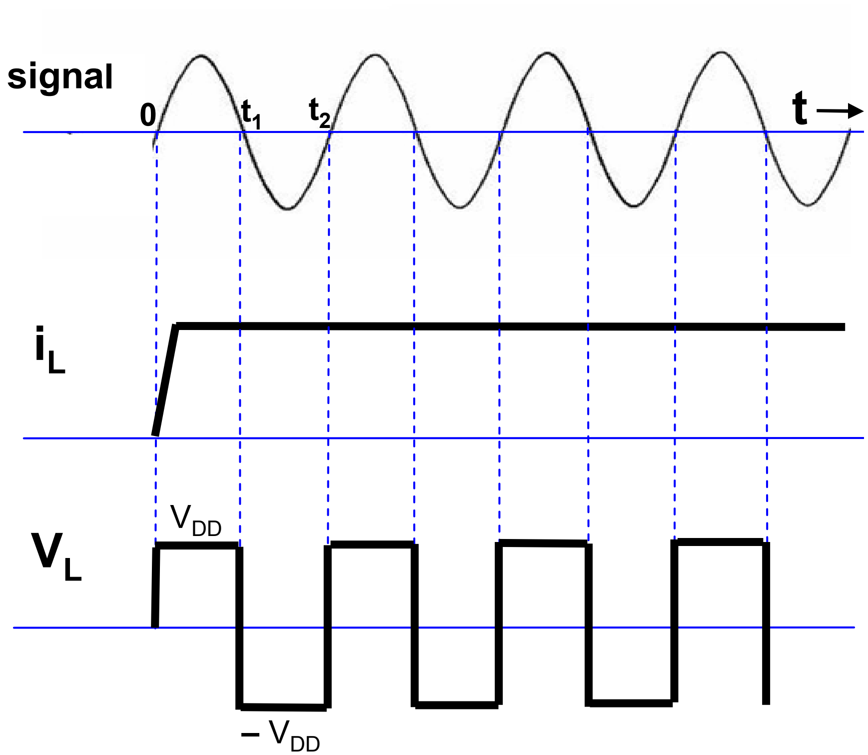
Note: The inductor current cannot change instantaneously so i_L continues to flow in the indicated direction.

For $t_1<t<t_2$ (switch open): with a suitably large value for L, the time constant L/R is large and i_L stays practically constant.

With i_L flowing as shown after $t=t_1$, *we see that the voltage V_L has changed its polarity to **negative***

For $t>t_2$ the process begins again.





Output Voltage Waveform of Idealized Class C Amplifier - 2

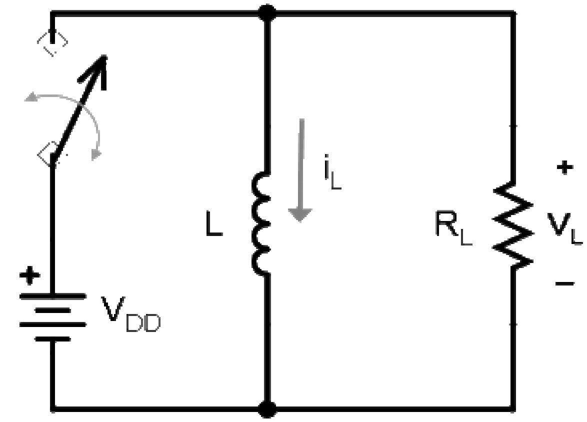
For $t_1<t<t_2$ (switch open):

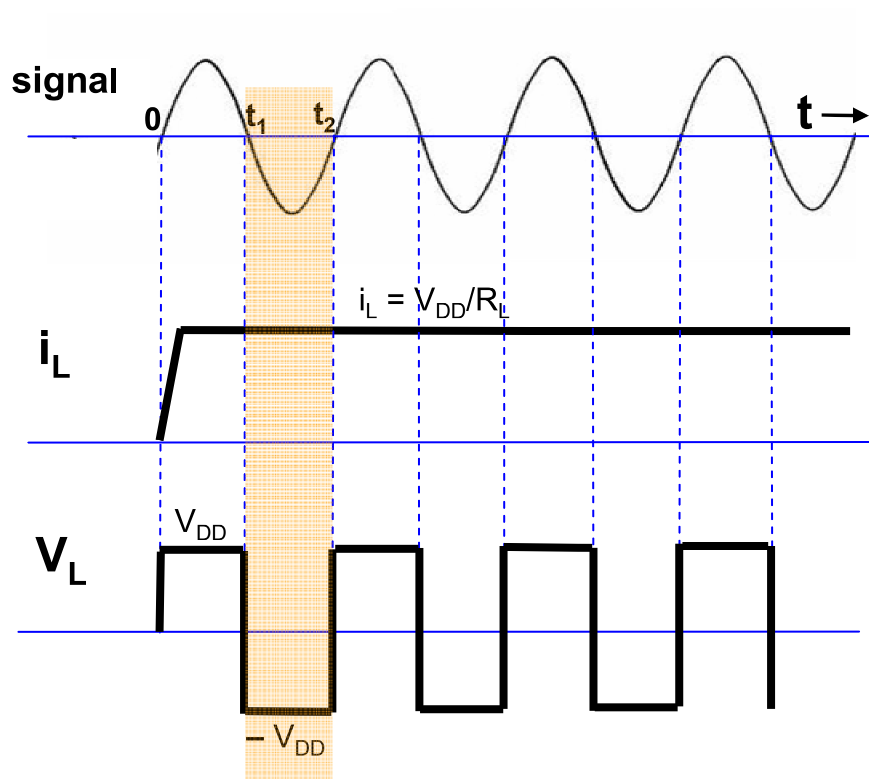
With i_L flowing as shown after $t=t_1$, *we see that the voltage V_L has changed its polarity to **negative** (i.e. to $-V_{DD}$)*

Why is the waveform for V_L symmetric?

Because the average value (DC value) of V_L must be zero inasmuch as V_L is the voltage across an inductor.

$-i_L \times R_L = -V_{DD}$, so $\mathbf{i_L = V_{DD}/R_L}$





Efficiency of Ideal Class C Amplifier

Efficiency = RF power out / DC power supplied

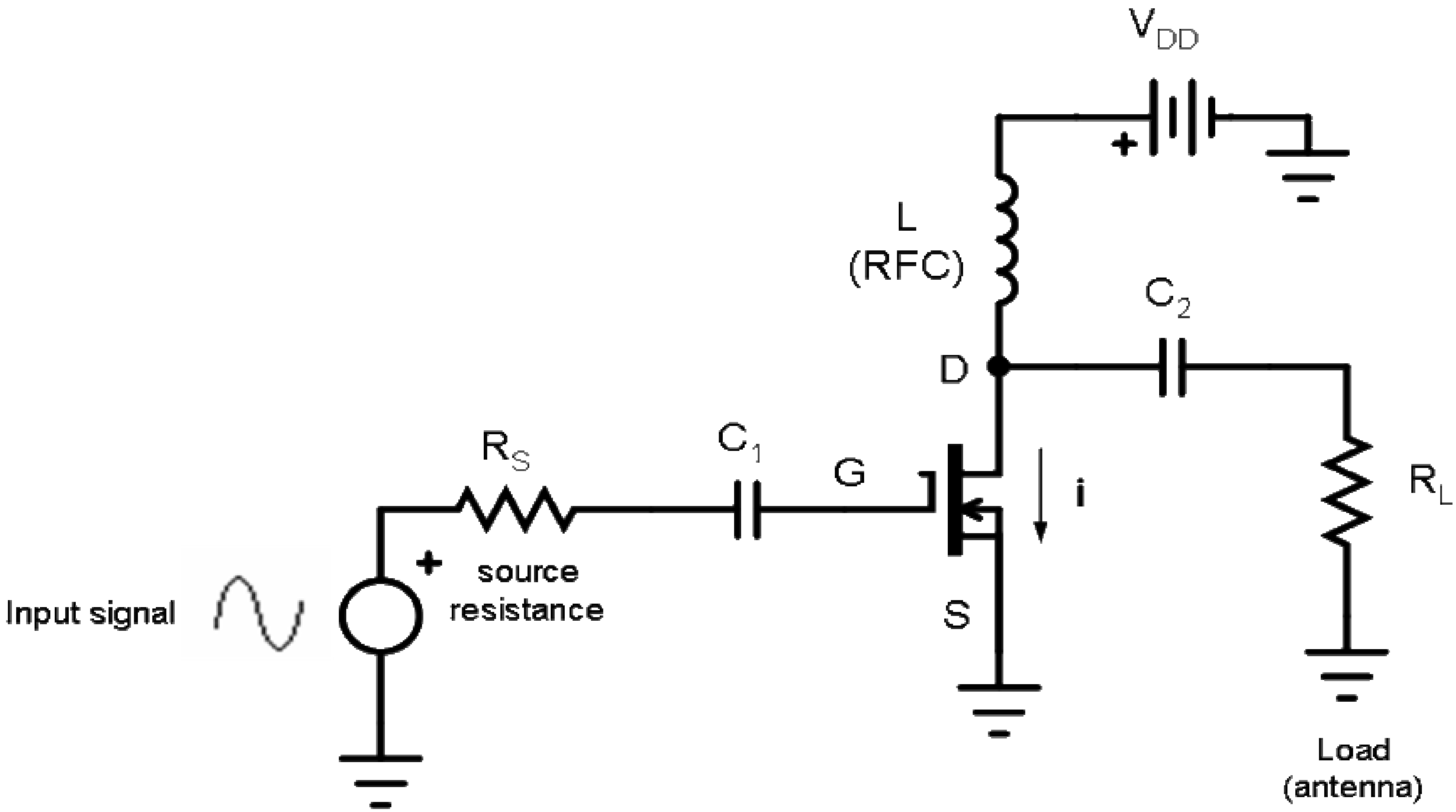
$= [V_{DD}^2 / R_L] \ / \ [V_{DD} \times i_L]$

$= [V_{DD}^2 / R_L] \ / \ [V_{DD} \times V_{DD}/R_L]$

= **100%**

Practical efficiencies realized: 50% - 80%

Simplified Class C Amplifier



Class C Amplifier Design Overview - 1

Device Selection

- Seek FETs that simulate ideal switch behavior
- Real devices have substantial input capacitance that limit switching speed
- Stability is also an issue

Input circuit

- Place "small" resistance R_P across gate-source terminals
- Effective input impedance to device+shunt $\approx R_P$
- Input time constant now small enough so switching can occur properly at signal frequencies
- Use impedance matching to transform source resistance (50Ω) to R_P

Class C Amplifier Design Overview - 2

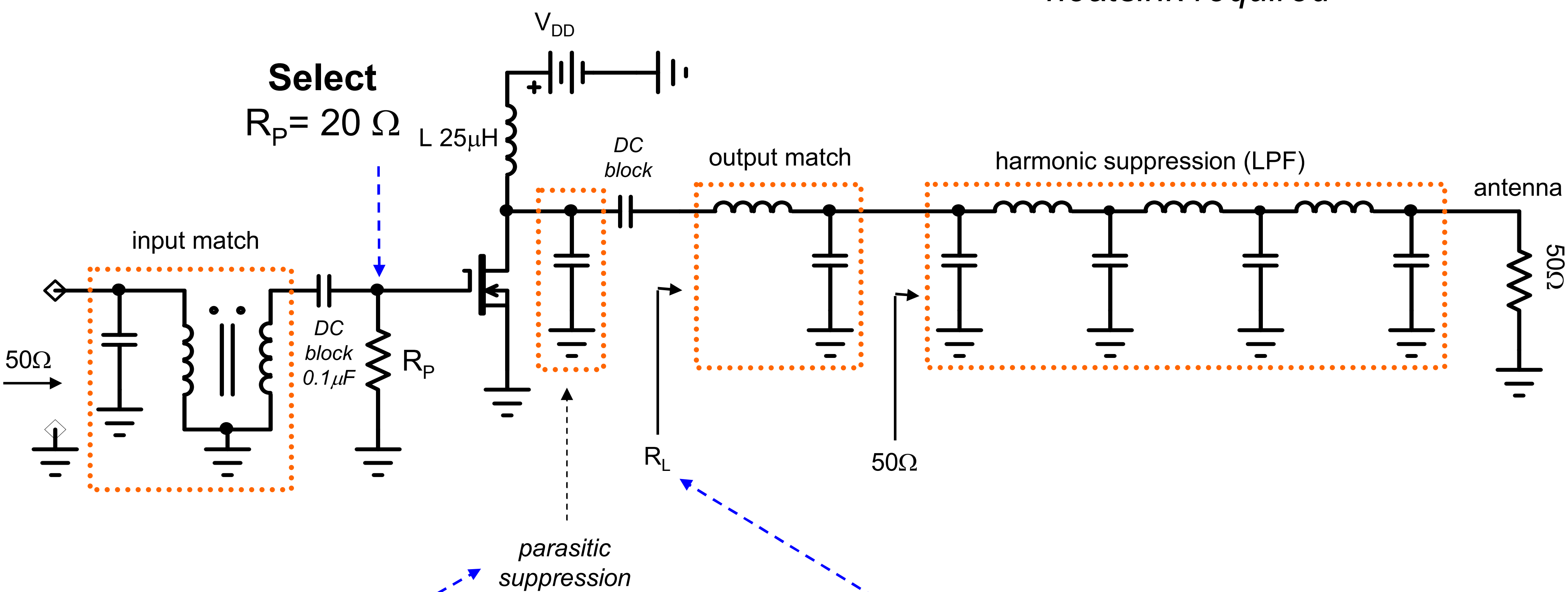
Output circuit

- Require additional circuitry (filtering) to cause voltage at load R_L to be sinusiodal
- Best case voltage at load is sinusoid of peak value V_{DD}
- Power to load $P_{out} = ½ [V_{DD}^2 / R_L]$
- Hence given power supply V_{DD}, must adjust R_L to achieve desired output power: $R_L = V_{DD}^2 / (2P_{out})$
- Slight adjustment of formula to compensate for $V_{DS(ON)} = I_D \times R_{DS}$ (R_{DS} from data sheet, estimate $I_D = P_{OUT}/V_{DD}$) *usually negligible*
- Instead, use a matching network to transform 50Ω (antenna load) to the required value
- Additional capacitance at drain eliminates spurious oscillation

Complete Practical Class C Amplifier

not shown: RF sensor for T/R switching

heatsink required



Rule of thumb:

make $|X_c| = 1/(\omega C) \approx 4 \times R_L$

I used 770 pF (300+470)
$|X_C| = 20.5\Omega$

$R_L = V_{DD}^2 / (2P_{out})$

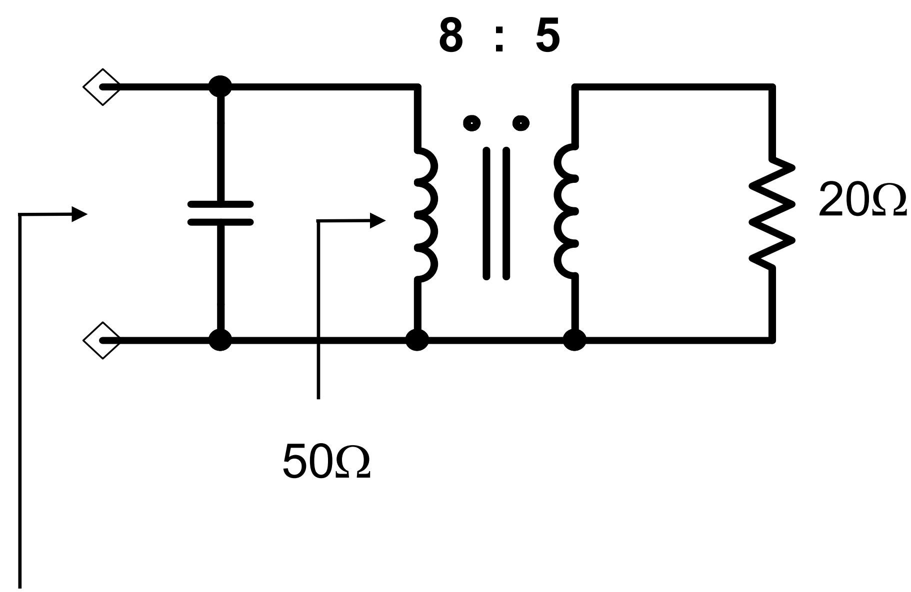
Select V_{DD}=24V, P_{out}=50 W

$R_L = 5.76\ \Omega$

Input Impedance Matching

We need to transform from 50Ω to 20Ω. A **ferrite transformer** easily achieves this (binocular core).

- I used type 61 ferrite; type 43 used by others; both ok
- Selected turns ratio 8:5 (Z ratio 64:25 = 2.56:1) transforms 20Ω to ≈50Ω
- With type 61 and indicated turns, measure 10.2μH and 3.94μH for windings (647Ω and 250Ω reactance)
- Evaluate the match on 50 Ω side by using an *antenna analyzer* – seek minimum SWR at 10.1 MHz
- Found that matching could be improved by adding 150pF capacitor – my eventual SWR was 1.4:1



for evaluation of match, connect antenna analyzer here

Output Impedance Matching - 1

- Need to transform from 50Ω to 5.76Ω

- Transformer matching does not work well here because of the relative high impedance ratio required (≈ 9:1) and the low value of one of the terminating impedances.

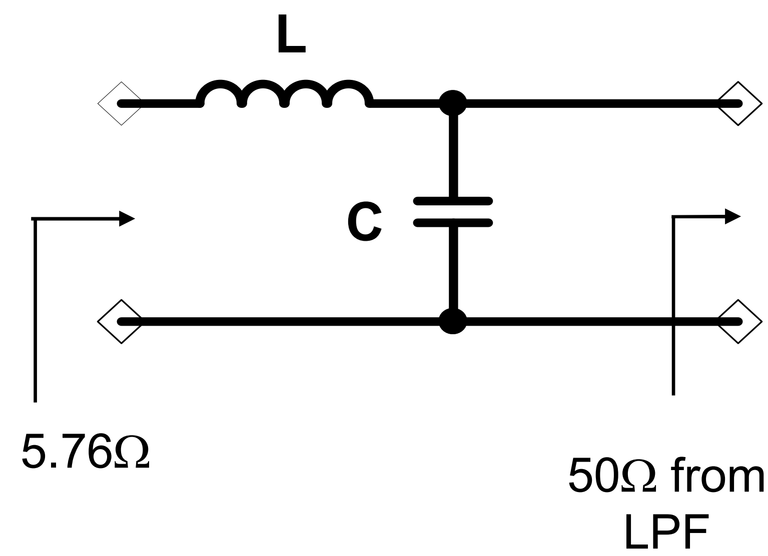
- Unsuccessful attempts with both types 43 and 61 ferrite cores

- Better method here: **LC impedance matching** (narrowband, but adequate for a given ham band)

- Design by (i) Smith Chart
  (ii) computer-aided design tools *-or-*
  (iii) online tools e.g.: http://leleivre.com/rf_lcmatch.html

Output Impedance Matching - 2

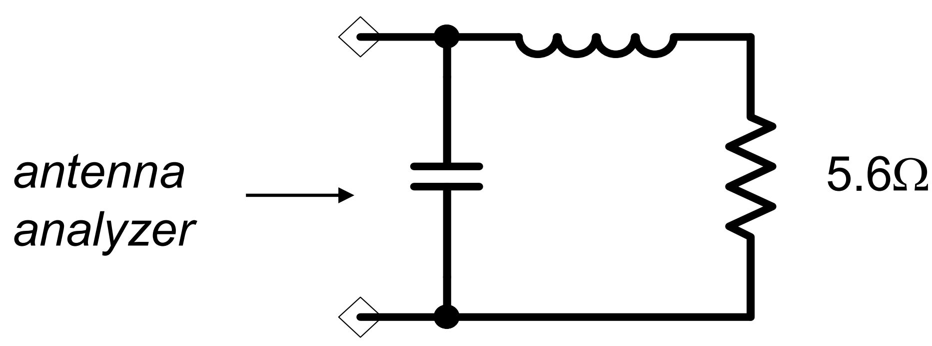
- Topology selection based on experience or trial and error (only 4 variations)



- My solution: L = 246.6nH
  C = 886pF

- Actual components: T80-6 core (yellow), 5 turns (≈220nH); 820pF silver mica capacitor

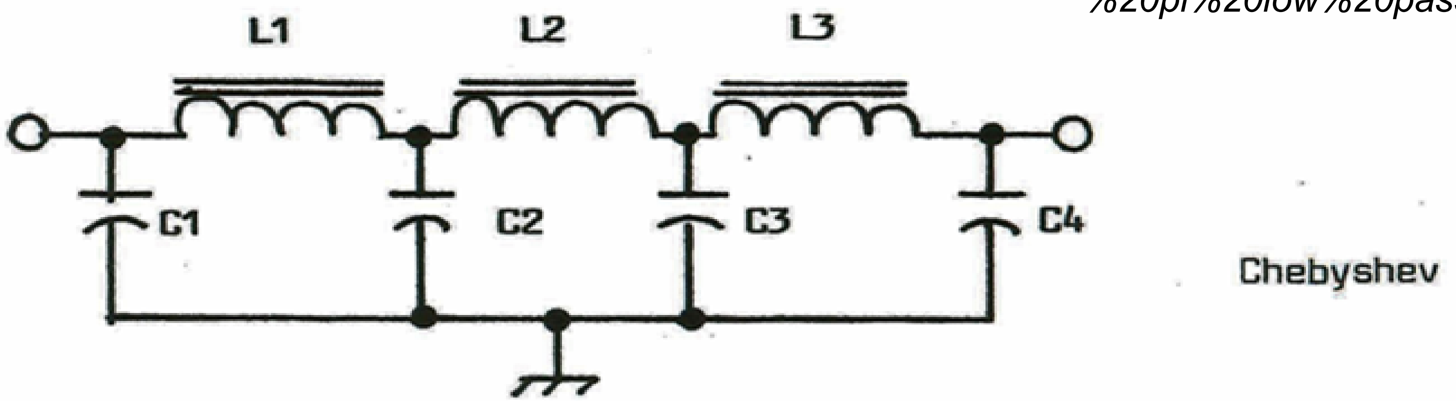
- Measured SWR < 1.2:1



Harmonic Suppression Filter

standard LPF design from tables or online tools e.g.:

http://www.calculatoredge.com/electronics/ch%20pi%20low%20pass.htm

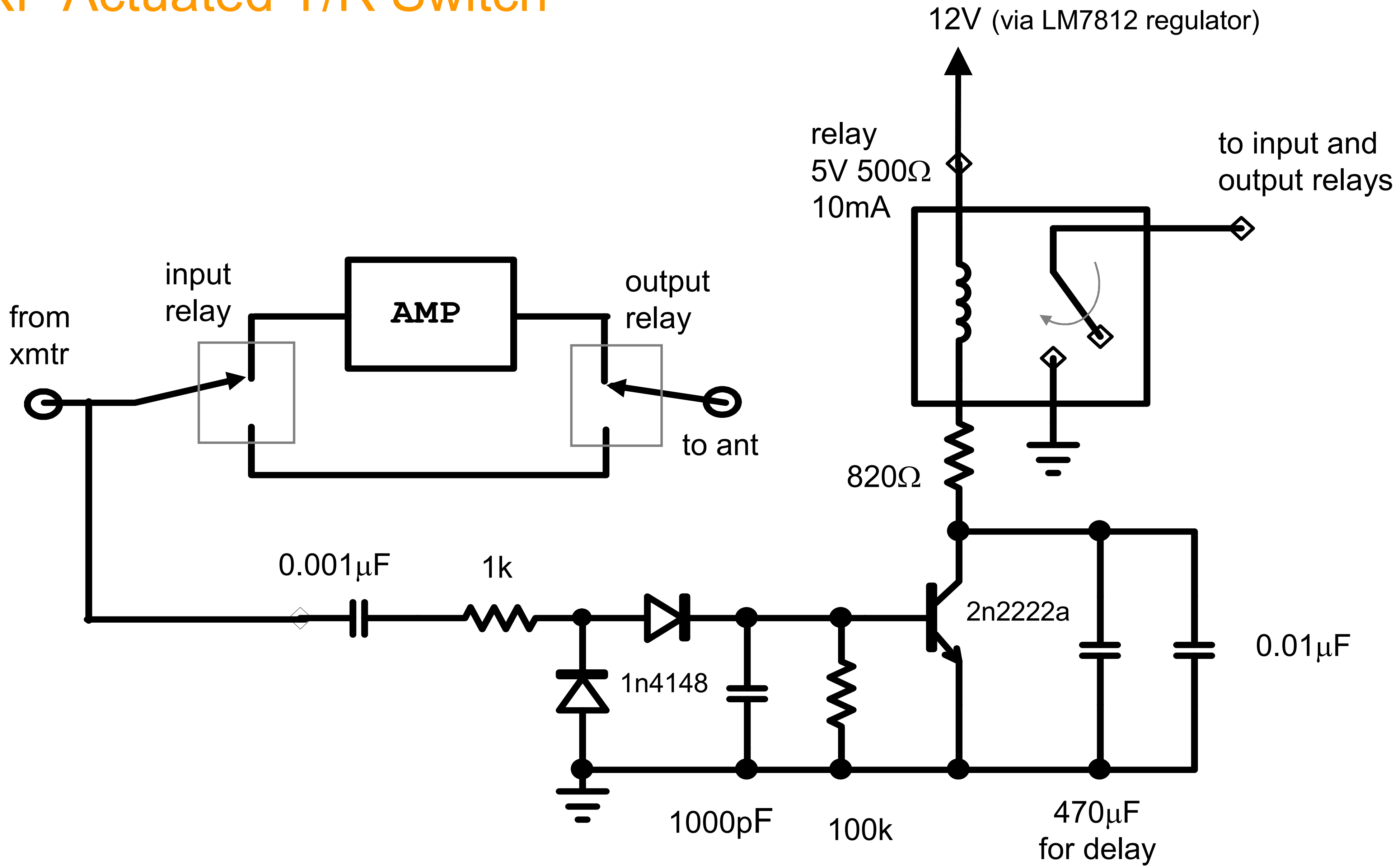


BAND (m)	C1, C4 (pF)	C2, C3 (pF)	L1, L3 (uH)	L2 (uH)	f_{co} (MHz)
80	510	1300	2.637	3.261	3.81
40	330	750	1.508	1.789	7.23
30	180	470	0.952	1.188	10.33
20	180	390	0.773	0.904	14.40
15	130	270	0.526	0.606	21.48
10	82	180	0.359	0.421	30.90

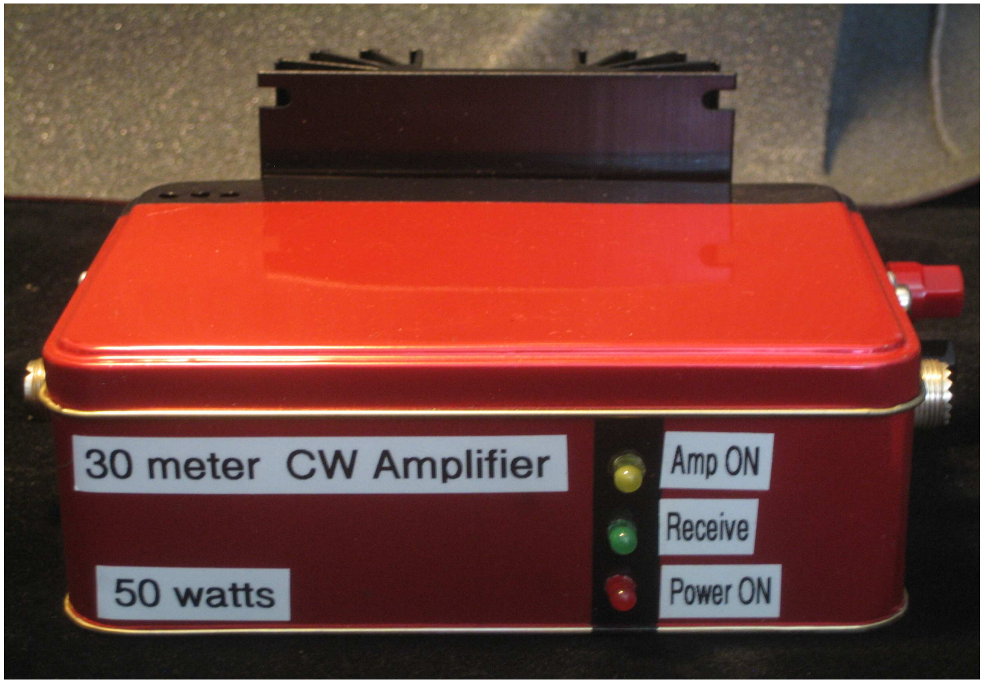
Component values for a 7-element low-pass harmonic filter. Inductors are wound on no. 6 powdered-iron toroids. Use standard equation for finding the required number of coil turns.

I used JW Miller solenoidal phenolic core inductors - from data sheet check Q, self-resonant frequency and power handling capacity

RF Actuated T/R Switch



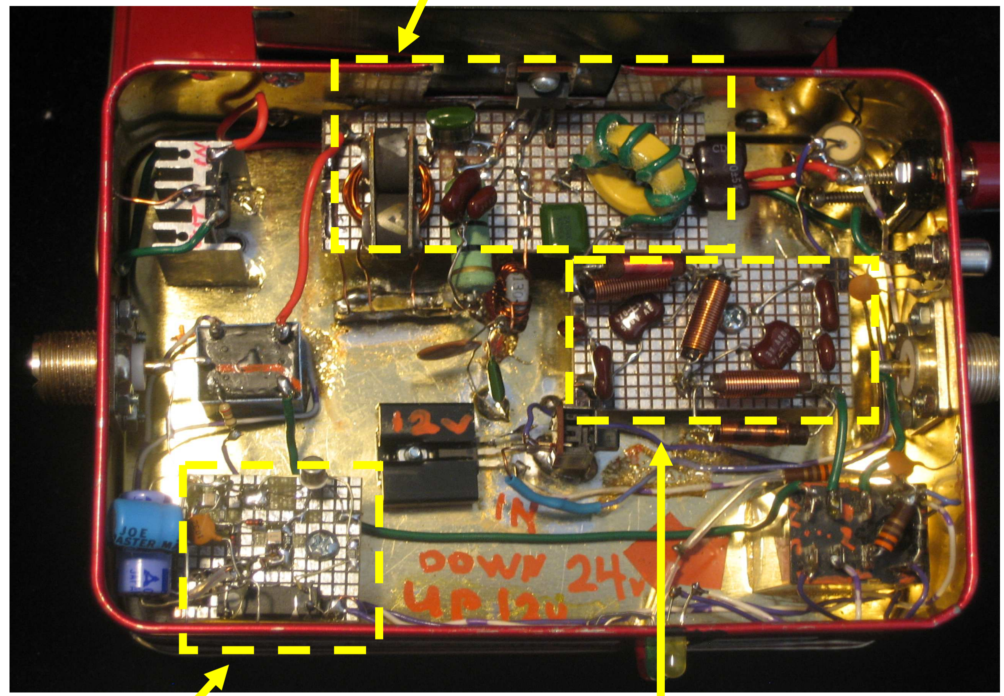
30m CW Amplifier – Construction - 1



6”

Complete Circuit

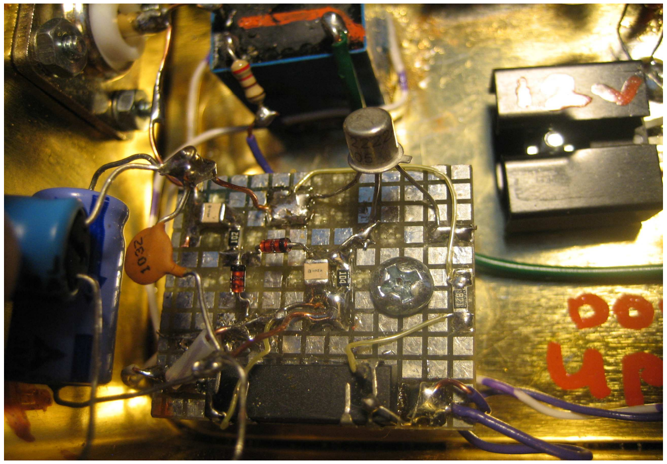
Input Match, FET, Output Match



RF Sensor for T/R Switching

Output Lowpass Filter

30m CW Amplifier – Construction - 2



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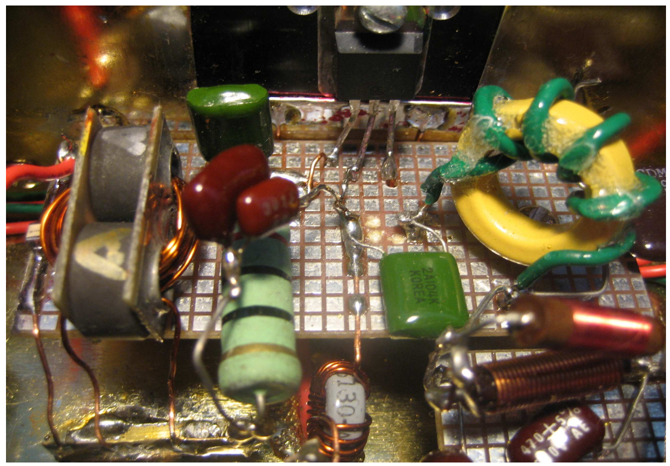

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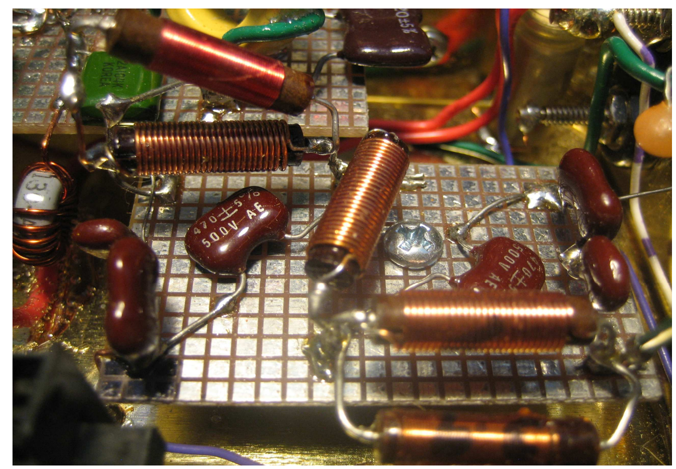

Output Lowpass Filter

Output Spectrum Measurement

down ≈40dB,
@ 60MHz

Summary and Conclusion

- Stated previous published experience for 20m class C amplifiers
- Expanded these ideas to 30m
- Explained building-block approach to the design
- Illustrated simple evaluation of the components
- Presented construction and operation