Designing, Building and Pitfalls of simple Class-E transmitters

A beginner's guide by a beginner experimenter

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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

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

*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 ($P_{\text{out}}$, $V_{\text{cc}}$, 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
\[ R = \left( \frac{(V_{CC} - V_o)^2}{P} \right)^{0.576801} \left( 1.0000086 - \frac{0.414395}{Q_L} - \frac{0.577501}{Q_L^2} + \frac{0.205967}{Q_L^3} \right) \]

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

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

\[ L2 = \frac{Q_L R}{2\pi f} \]
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)
- \[ Xc = \frac{1}{2\pi fC} \]
- 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

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

Always check the correct datasheet for your component!
Design: calculations

Class-E RF Amplifier

Based on the Nathan Sokal WA1HQC equations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output</td>
<td>25 Watts</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>12.5 Volts</td>
</tr>
<tr>
<td>Saturation Voltage</td>
<td>0.2 Volts</td>
</tr>
<tr>
<td>Loaded Q</td>
<td>5</td>
</tr>
<tr>
<td>Frequency</td>
<td>137777 Hz</td>
</tr>
<tr>
<td>Feed Choke</td>
<td>0.00047 HEN</td>
</tr>
</tbody>
</table>

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

**Load Resistance**: 3.126 Ω

<table>
<thead>
<tr>
<th>Capacitor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>79.055 nF</td>
</tr>
<tr>
<td>C2</td>
<td>98.846 nF</td>
</tr>
<tr>
<td>L2</td>
<td>18.058 uH</td>
</tr>
</tbody>
</table>
Implementation: L1

- Not critical!
- 30x the load impedance
- Ferrite toroid
Implementation: C1, C2

- $C1 = C_{\text{oss}} + \text{Extra capacitance}$
- 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:
  - $N_1/N_2 = \sqrt{Z_1/Z_2}$
- 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

<table>
<thead>
<tr>
<th>V_CE Relative to V_CE(wn) at Time of Zero Slope</th>
<th>V_CE Slope at Transistor Turn On</th>
</tr>
</thead>
<tbody>
<tr>
<td>More Positive; Decrease C1/C2</td>
<td>Positive: Increase (C1 Series C2)</td>
</tr>
<tr>
<td></td>
<td>Increase C2</td>
</tr>
<tr>
<td>Equal; Keep Same C1/C2</td>
<td>Nominal Colle E Waveform</td>
</tr>
<tr>
<td></td>
<td>Decrease C1 and C2 in Same Proportion</td>
</tr>
<tr>
<td>More Negative; Increase C1/C2</td>
<td>Increase C1</td>
</tr>
</tbody>
</table>
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

VK1SY 50 W, 160 m transmitter
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?