

We4C-4

200-W 13.56-MHz Class-E PA with Gate-Driver ICs

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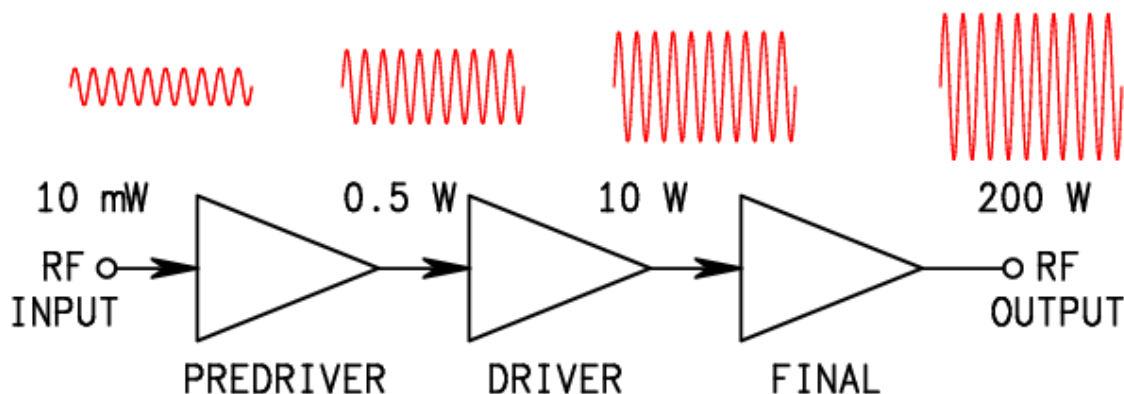
200-W 13.56-MHz Class-E PA with Gate-Driver ICs

- Introduction
- Concepts
- Matched loads
- Mismatched loads
- Other frequencies
- Conclusions

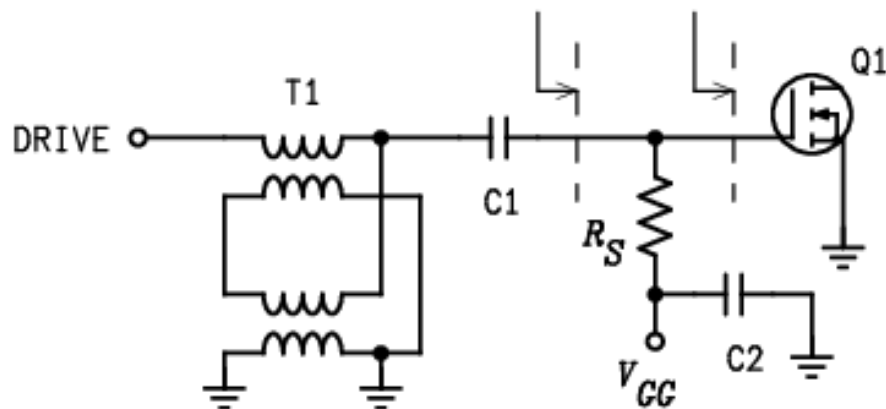
Why 13.56 MHz ?

- RF heating
- Cancer treatment
- Skin tightening
- Plasma generation – RF lighting, semiconductor process
- Clothes drying
- Welding plastic pipe
- Close to 20-meter ham band
- Other HF ISM 6.78, 27.12 MHz
- Communications 1.8 – 30 MHz

TRADITIONAL RF CHAIN



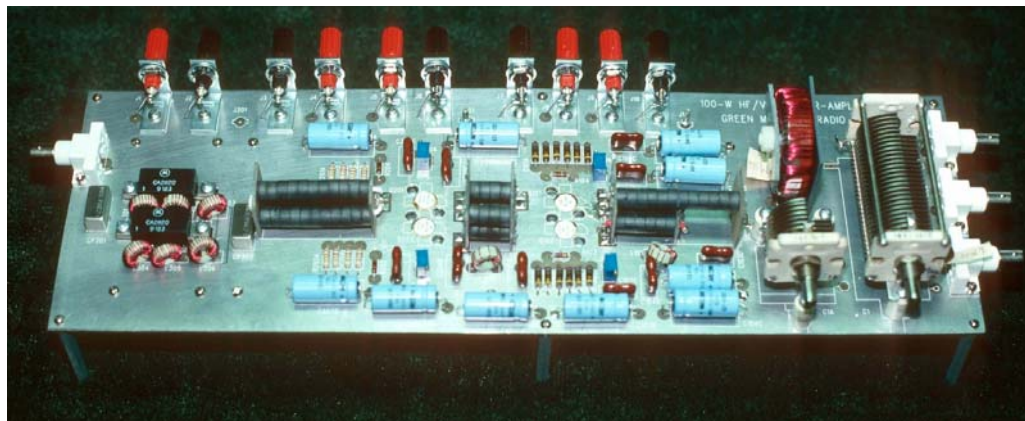
$$Z \approx R_S \quad Z_G = \text{HIGH}$$



- Progressively higher power
- Broadband transformers, ferrite-loaded
- Gate-swamping resistors

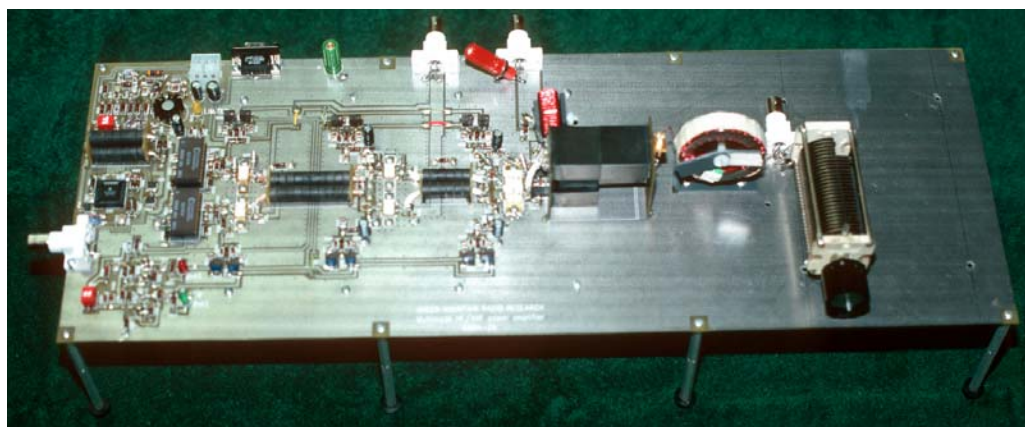
EXAMPLE HF/VHF RF CHAINS

10 mW



100 W

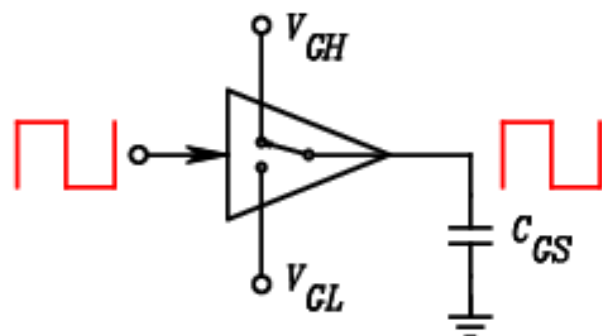
10 mW



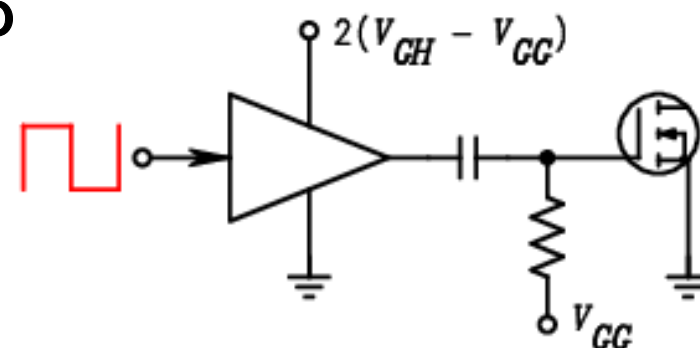
175 W

GATE DRIVERS

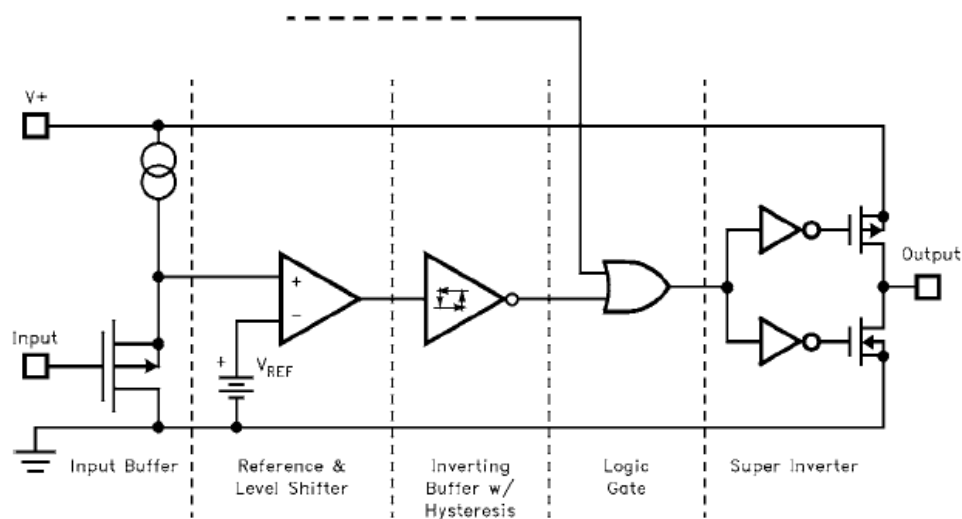
BASIC OPERATION



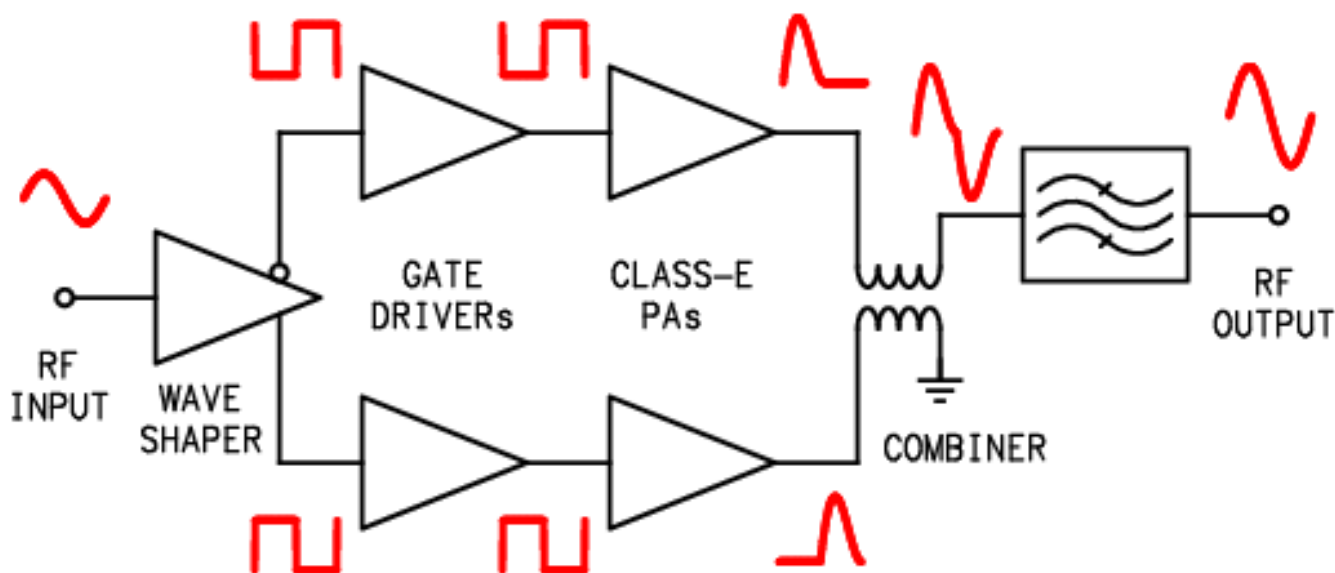
AC COUPLED



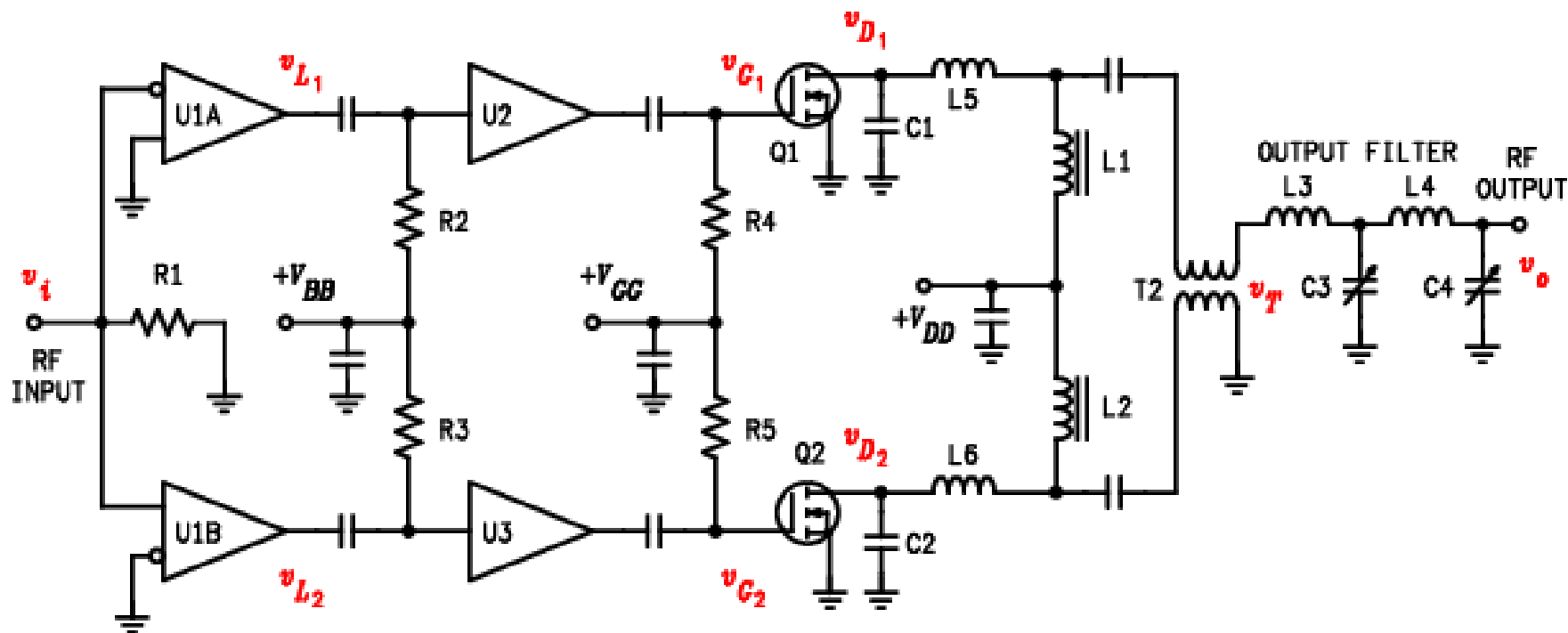
INTERNAL WORKINGS



AMPLIFIER BLOCK DIAGRAM



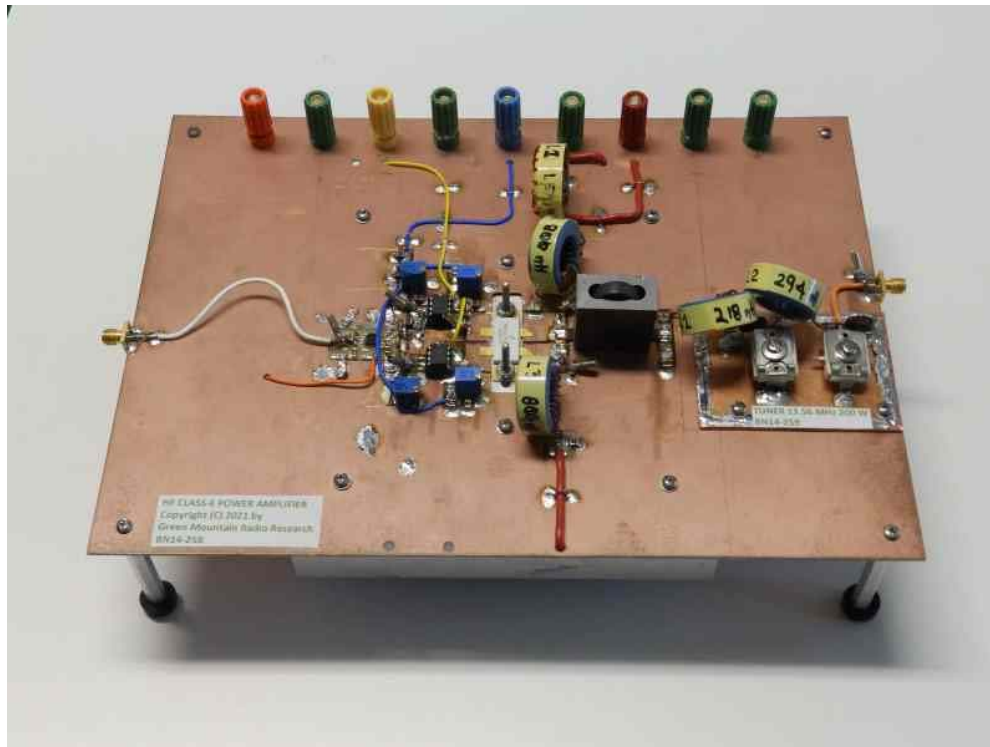
- LVDS line receivers
- CMOS gate drivers
- 50-V LDMOS gemini RF-power FET
- Ferrite-loaded balun
- LCLC output filter ($6.25 + j7.2 \Omega$)



- Push-pull class E
- Bias GDs and FETs at threshold
- $3.125 + j3.6 \Omega$ at drains
- 200 W with $V_{DD} = 35 \text{ V}$

PROTOTYPE

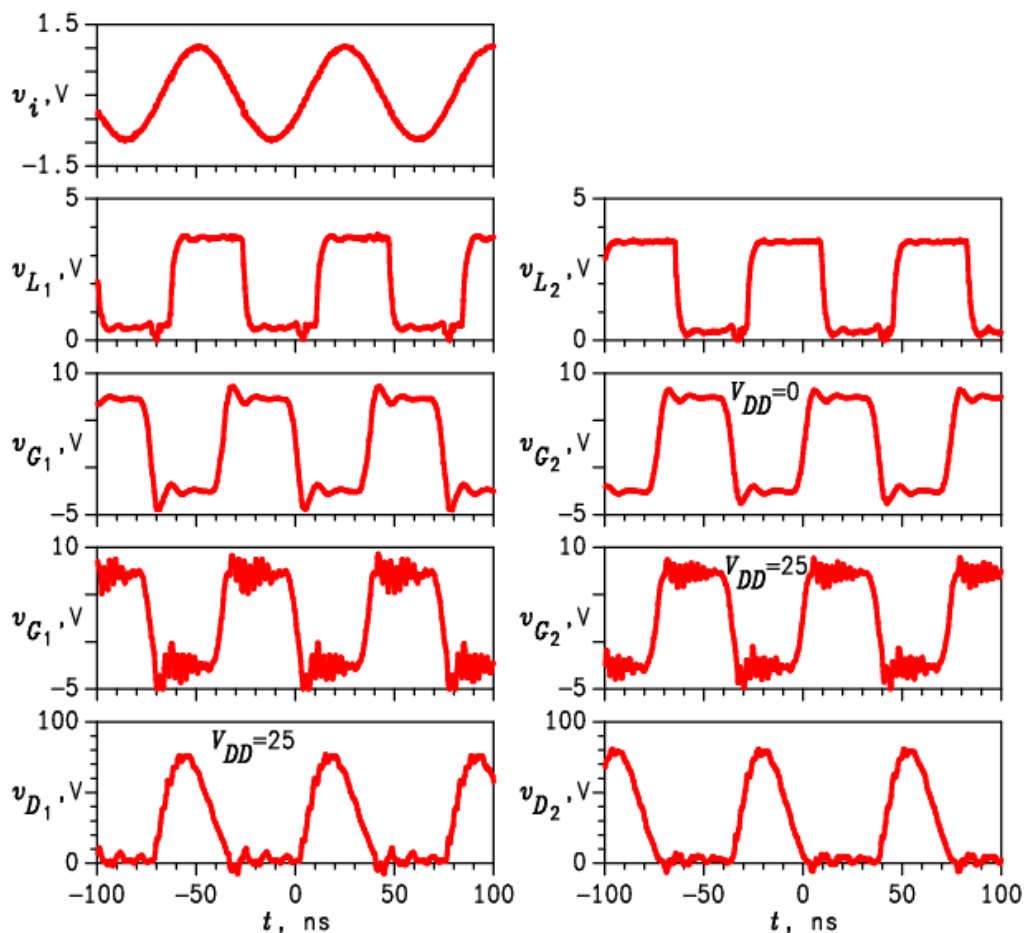
10
mW



200 W

- Compact
- Separate supplies
- Gate drivers socketed
- Changeable output filter

PROTOTYPE



Input

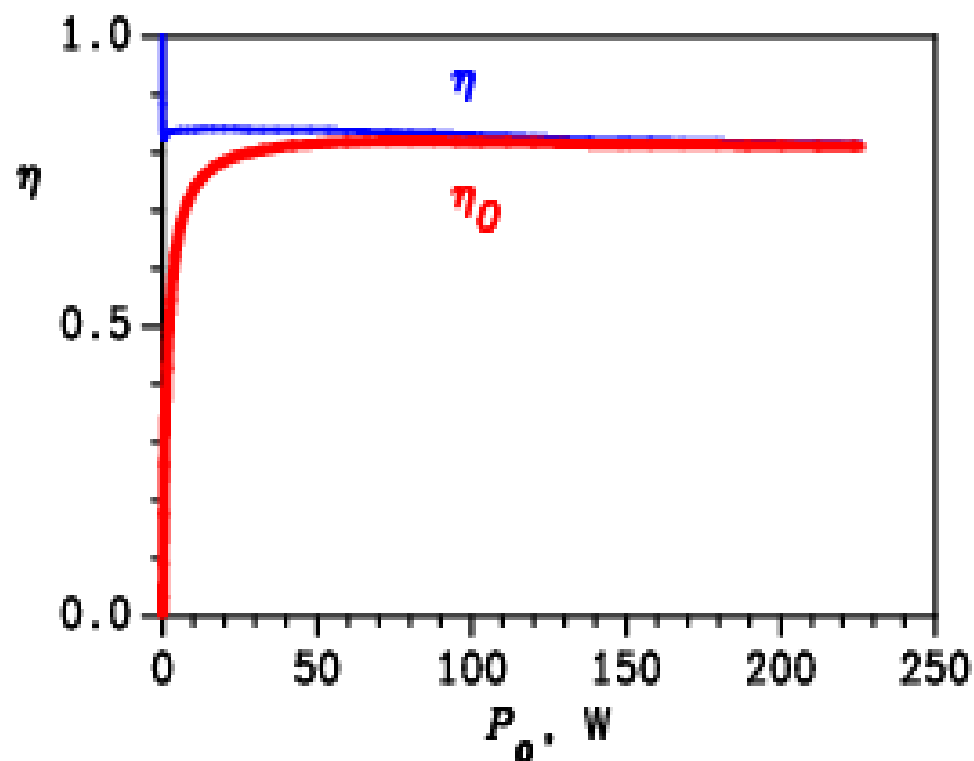
Wave shaper

Gates – $V_{DD} = 0$

Gates – $V_{DD} = 25$ V

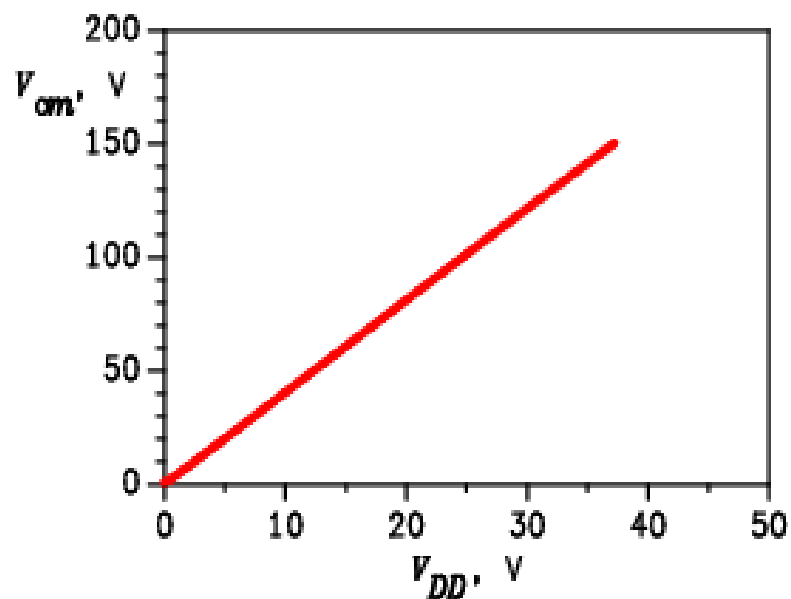
Drains – $V_{DD} = 25$ V

POWER AND EFFICIENCY

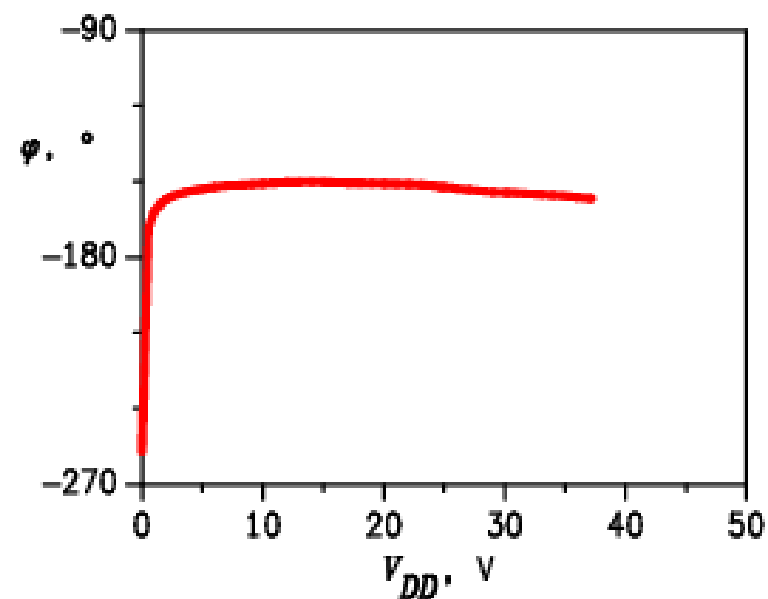


- $\eta = P_o / P_i$
- $\eta_o = P_o / (P_i + P_{GD} + P_{WS})$
- $\eta_o > 70\%$ $P_o > 8$ W
- $\eta_o > 80\%$ $P_o > 32$ W
- $\eta_o > 81\%$ $P_o > 32$ W

MODULATION CHARACTERISTICS

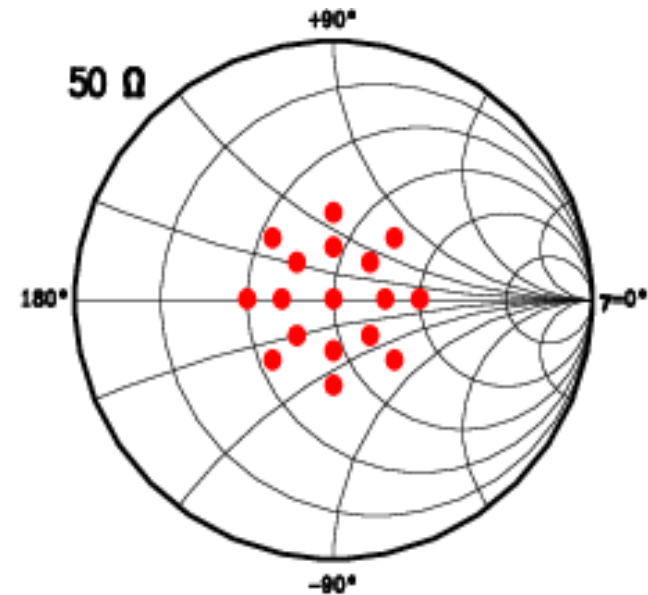
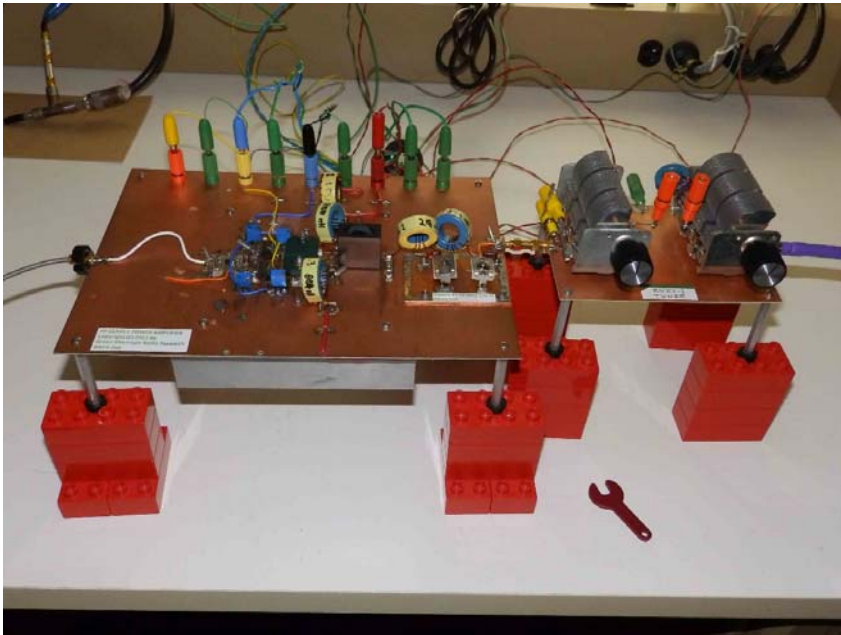


AM linearity 0.14% rms error
(57 dB C/I for two tone)
Feedthrough 6 mW (-45 dBc)
Limited drive-mod capability



4° for 2.6 – 200 W
EER
Precise amplitude & phase

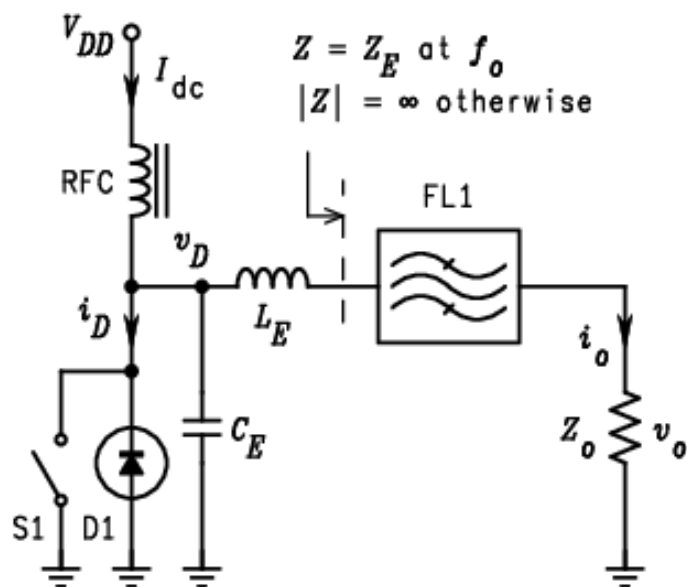
MISMATCHED LOADS



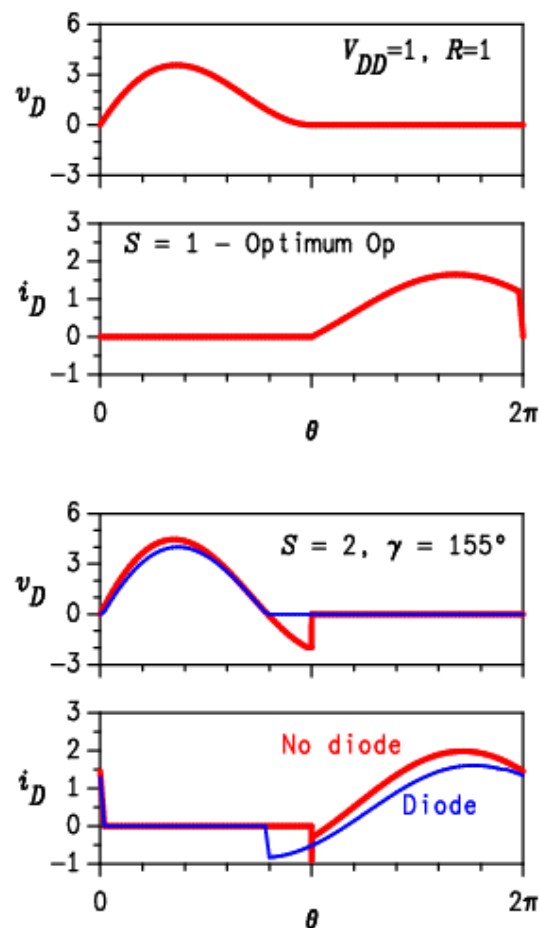
- Reality for most ISM aps
- Often impedance varies rapidly
- Maintaining match difficult

- Pi-net tuner
- SWR = 1.5, 2
- 8 points on each circle

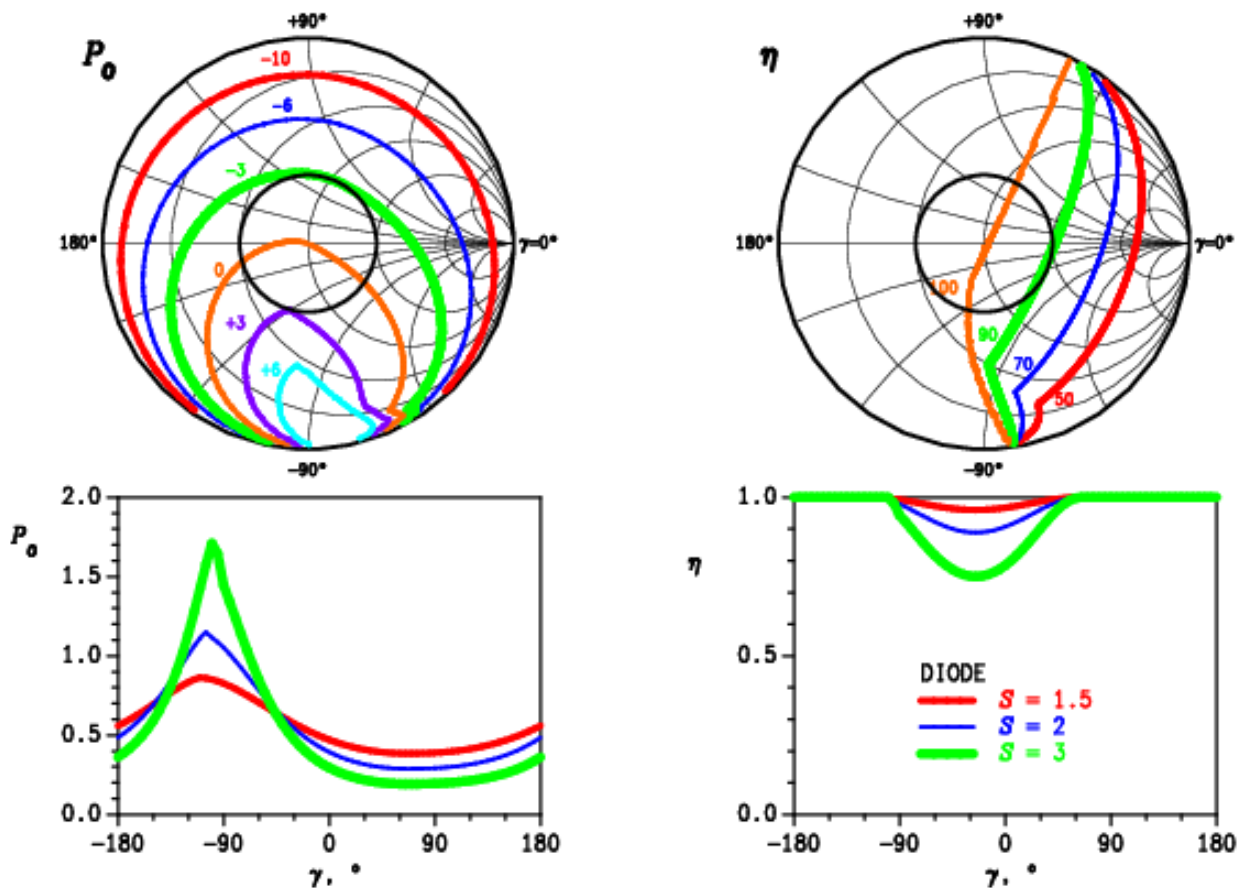
CLASS E WITH MOSFET



- Bidirectional drain current
- Reverse diode inherent
- No negative drain voltage
- Shortens off time

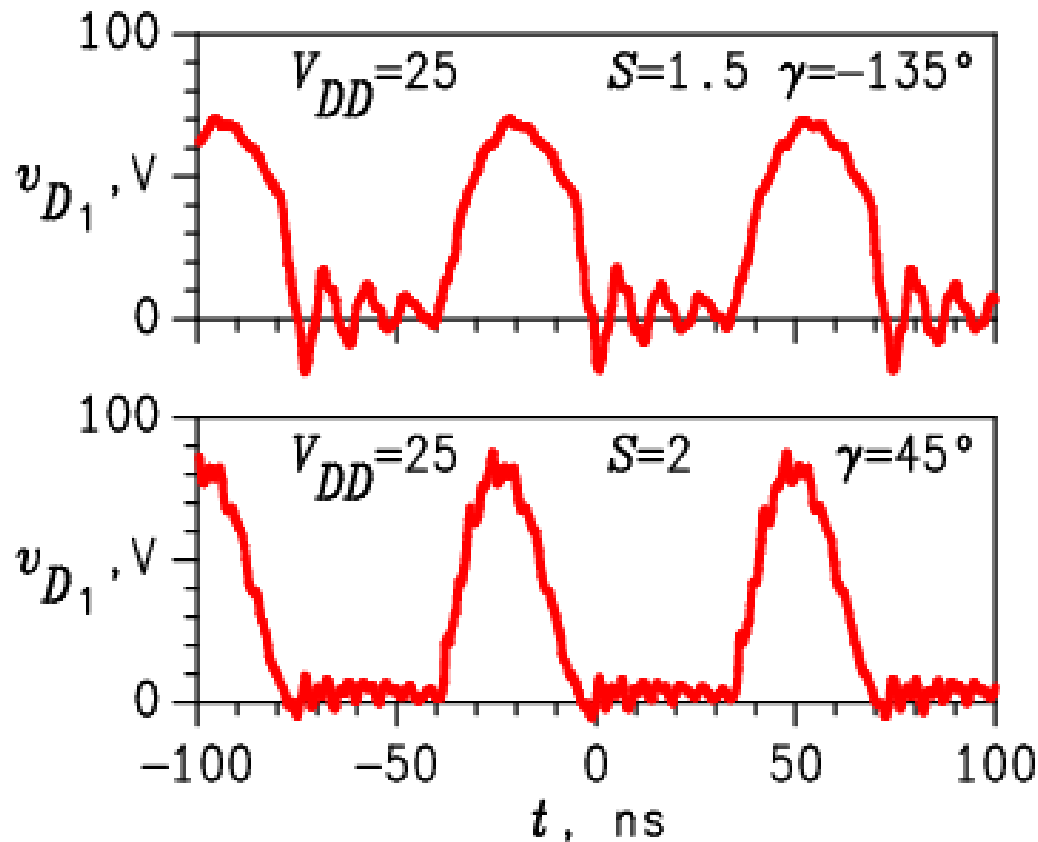


NEW THEORY - MOSFET CLASS E



- $V_{DD} = R = 1$
- Negative drain current
- No negative drain voltage

CLASS E WITH MOSFET

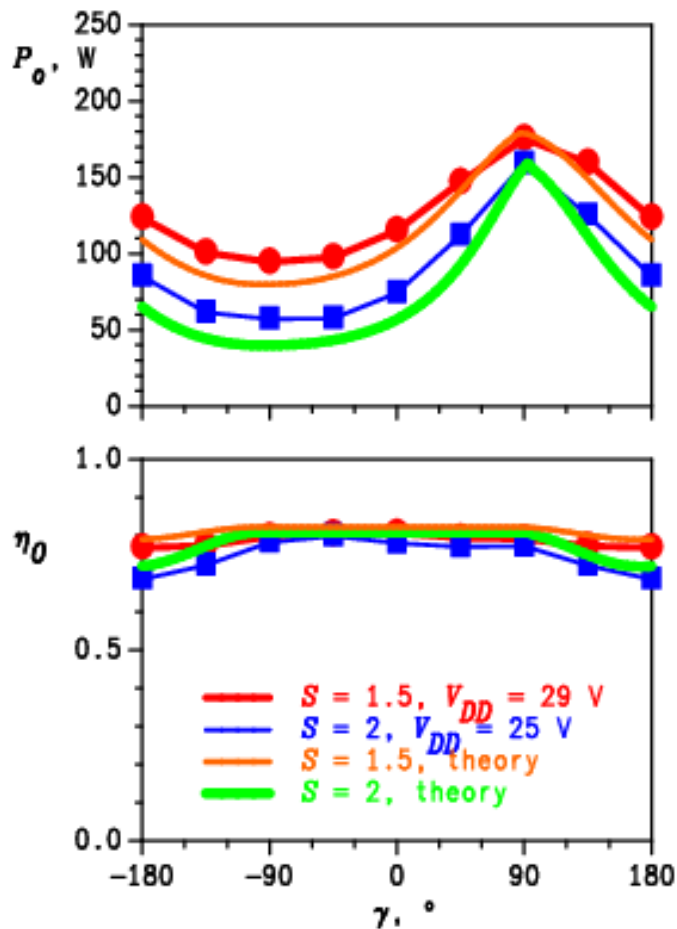


- FET turns on with v_D positive
- Capacitive discharge
- Drop in efficiency
- Off time unchanged

- Diode clamps v_D at 0
- No capacitive discharge
- Efficiency ideally high
- Off time shortened

Note: Transformer and filter rotate γ by 197° .

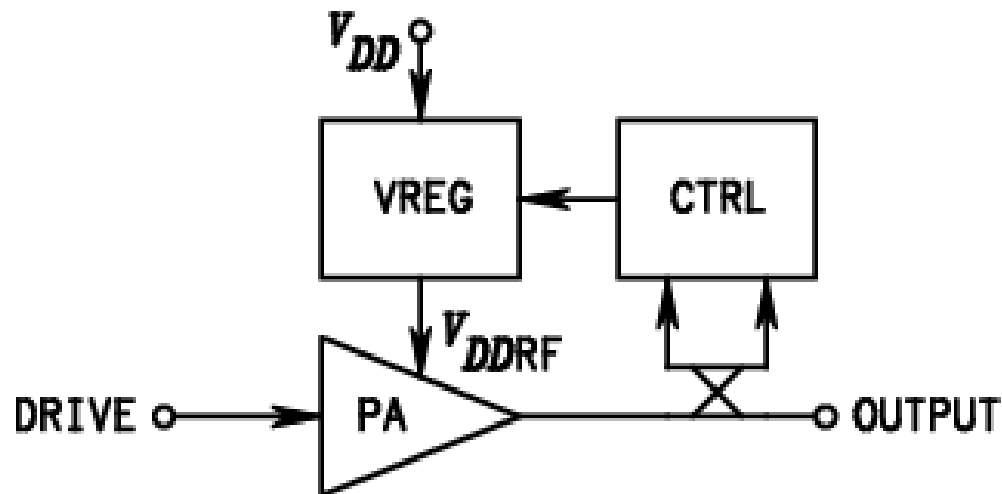
POWER AND EFFICIENCY



- Only one dip in efficiency
- High efficiency in diode region
- Maximum v_D reduced
- $\text{SWR} = 1$
200 W, 81%
- $\text{SWR} = 1.5$
95 - 175 W, 76 - 80%
- $\text{SWR} = 2$
57 - 159 W, 68 - 78%

Note: Transformer and filter rotate γ by 197° .

POWER CONTROL



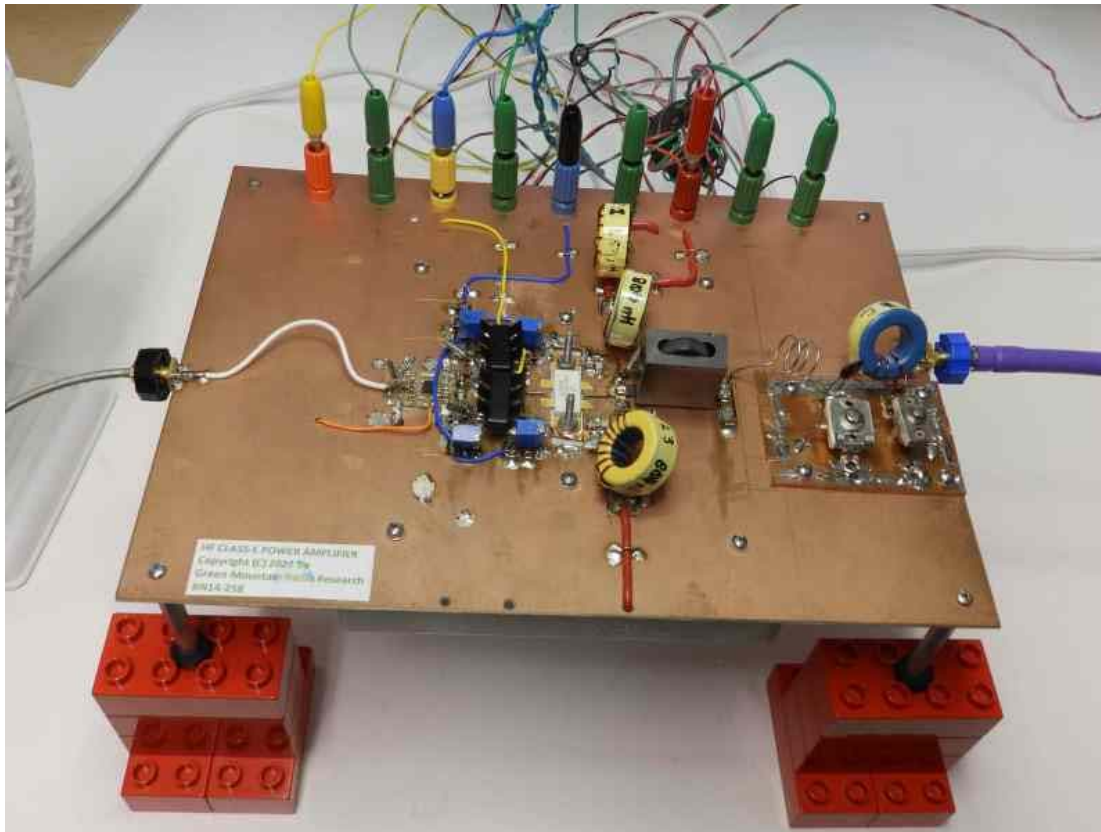
DIODE ACTION

- Sort of an autotuner
- Maintains efficiency but
- Power varies

CONSTANT POWER

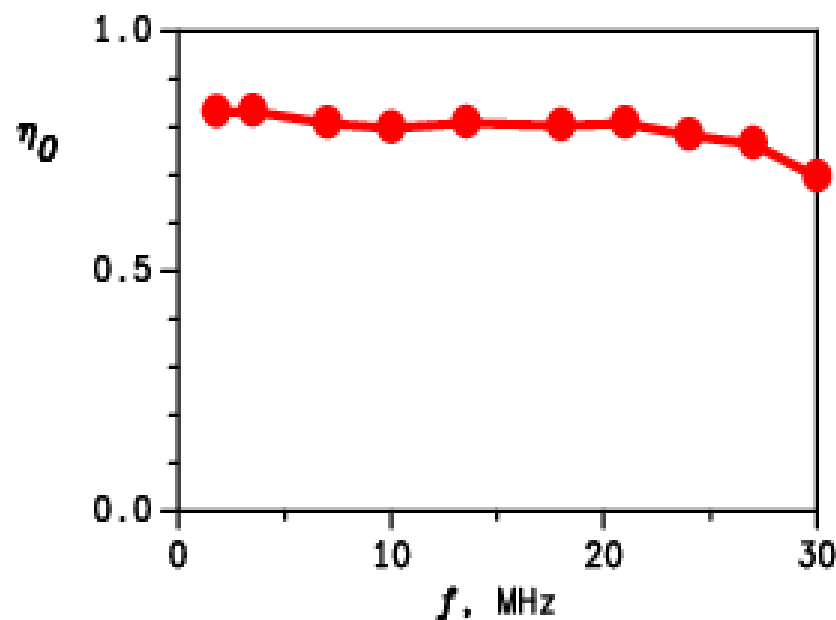
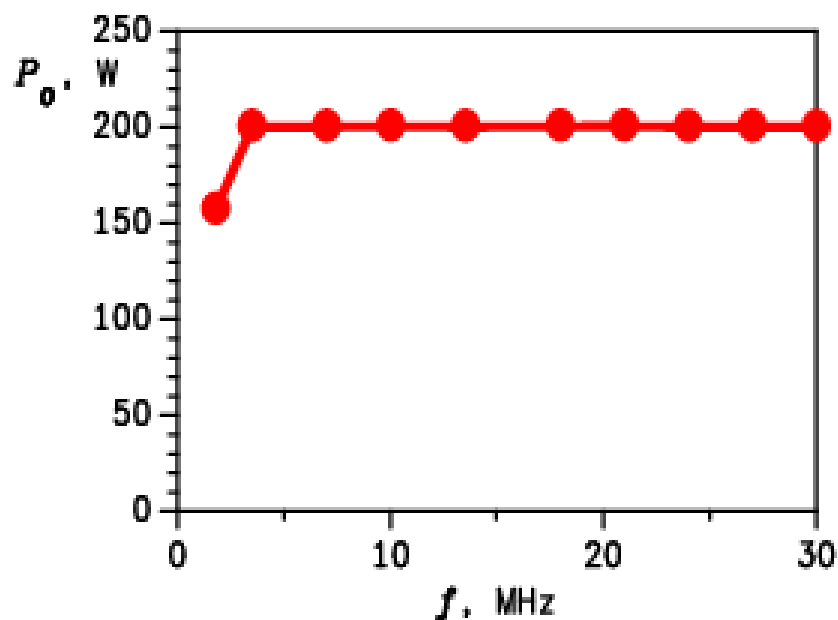
- Measure forward power
- Switching regulator
- Adjust V_{DD} by feedback

OTHER FREQUENCIES



- Change drain capacitors
- Change output tuner
- Heat sinks on gate drivers
- No retuning of drivers

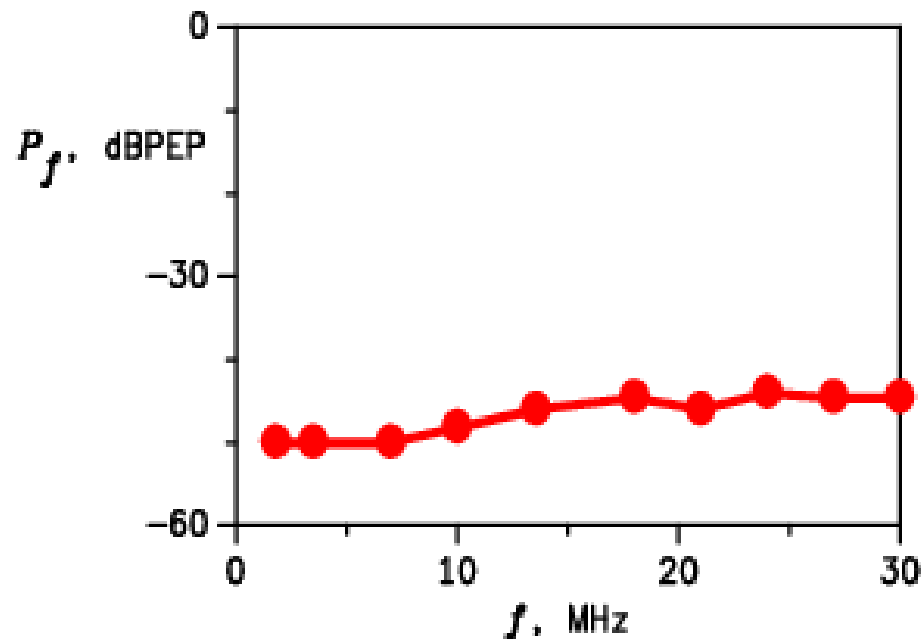
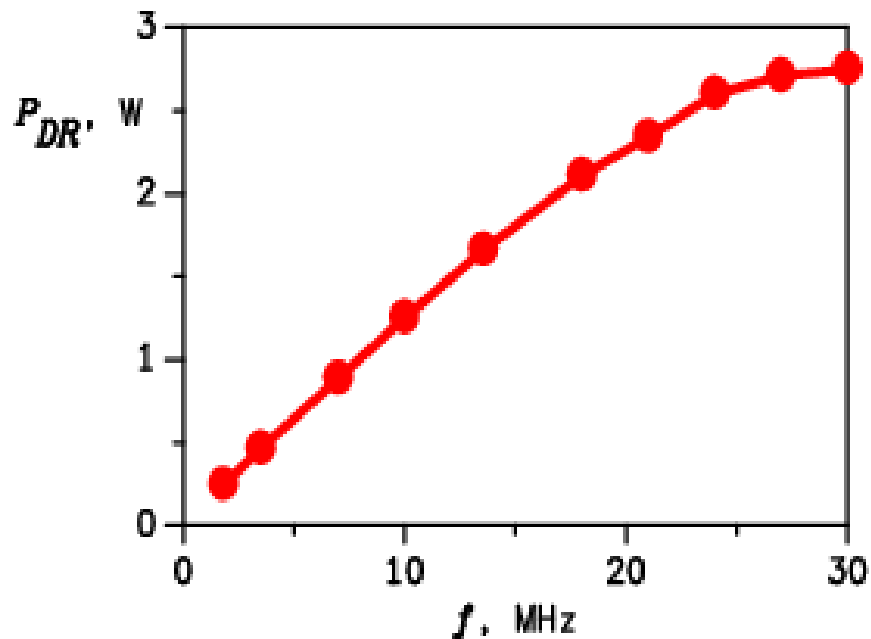
POWER AND EFFICIENCY



- 200 W, 3.5 – 30 MHz
- 175 W, 1.8 MHz
- Culprit: Transformer

- 83 – 76%, 1.8 – 27 MHz
- 70%, 30 MHz
- Culprit: Drive

DRIVE POWER AND FEEDTHROUGH



- Maximum 2.75 W
- Conventional 3 – 4 W

- Maximum -45 dBPEP
- Typical SSB or I/Q mixer -40 dBc

DEMONSTRATED

- HF class-E PA with LDMOS and gate drivers
- 175 – 200 W, 93 – 70 % with matched load
- Efficiency > 68% for SWR up to 2
- Drive chain simple, small, low-cost, lower power
- ISM applications 6.78, 13.56, 27.12 MHz
- Communication applications 1.8 – 30 MHz

FURTHER INVESTIATIONS

- Improve layout and transformer
- Exploit the diode effect