HIGH-EFFICIENCY RF POWER AMPLIFIERS AND TRANSMITTERS

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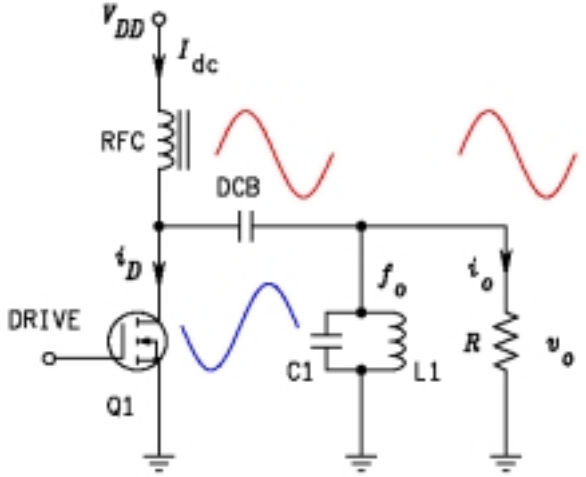
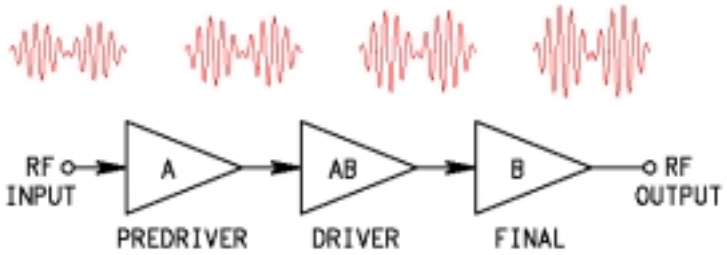
1. Introduction
2. Power Amplifiers
3. Architectures

AMPLIFIERS vs. ARCHITECTURES

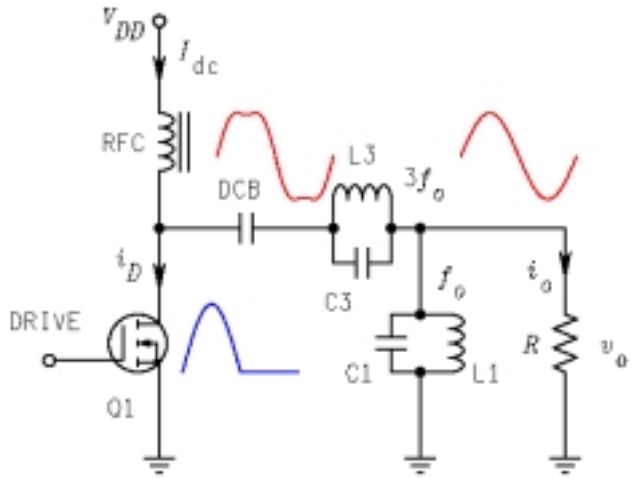
CLASS-A PA



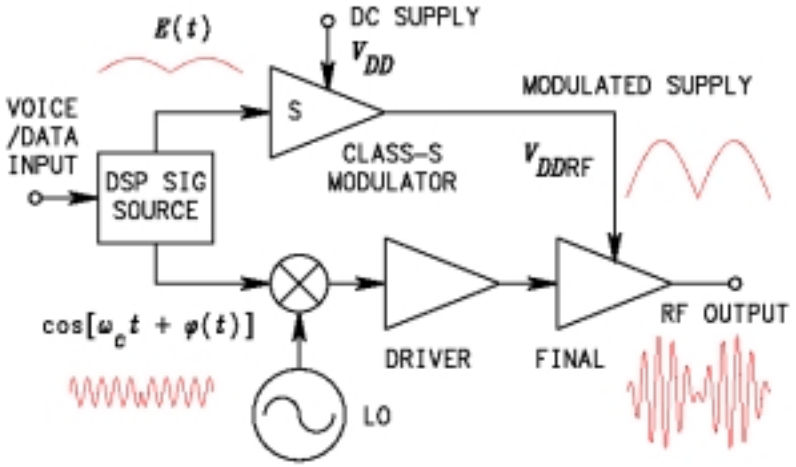
LINEAR ARCHITECTURE



CLASS-F PA

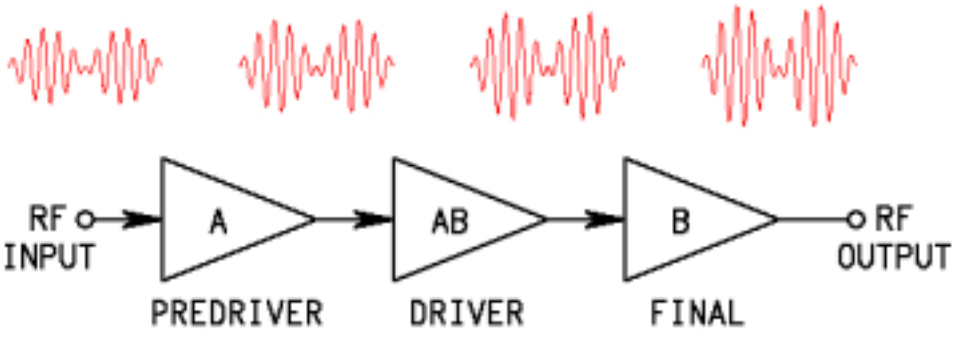


KAHN ARCHITECTURE

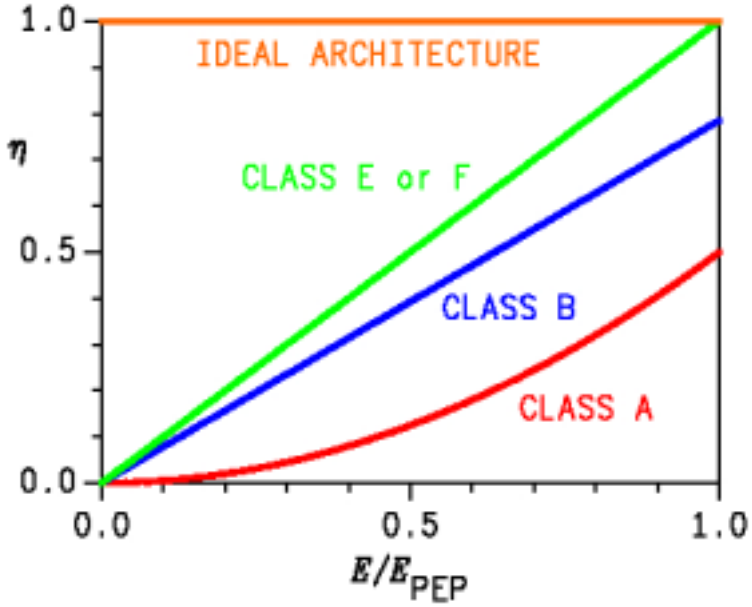


INSTANTANEOUS EFFICIENCY

LINEAR-AMPLIFIER CHAIN



INSTANTANEOUS EFFICIENCY

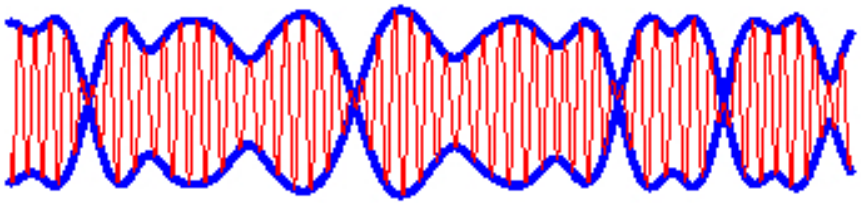


$$\eta = P_o / P_i$$

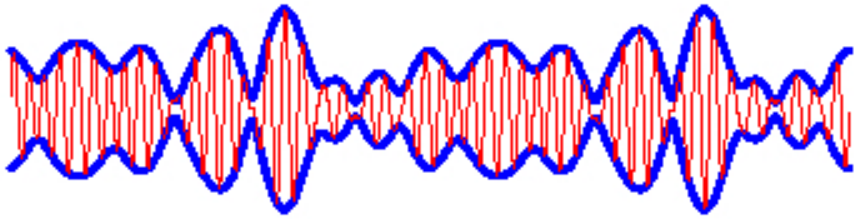
$$\eta_A = (P_o - P_{DR}) / P_i \qquad \eta_O = P_o / (P_i + P_{DR})$$

AVERAGE EFFICIENCY

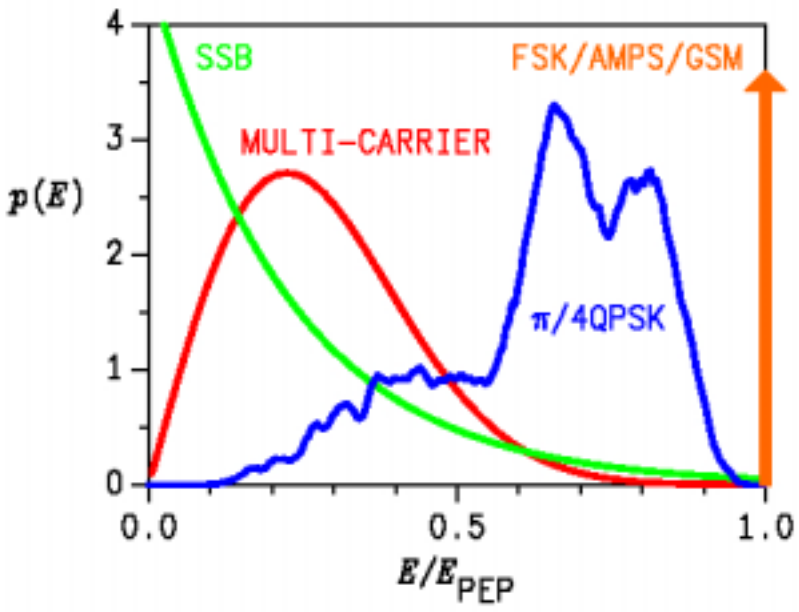
SRRC



OFDM



ENVELOPE PDF

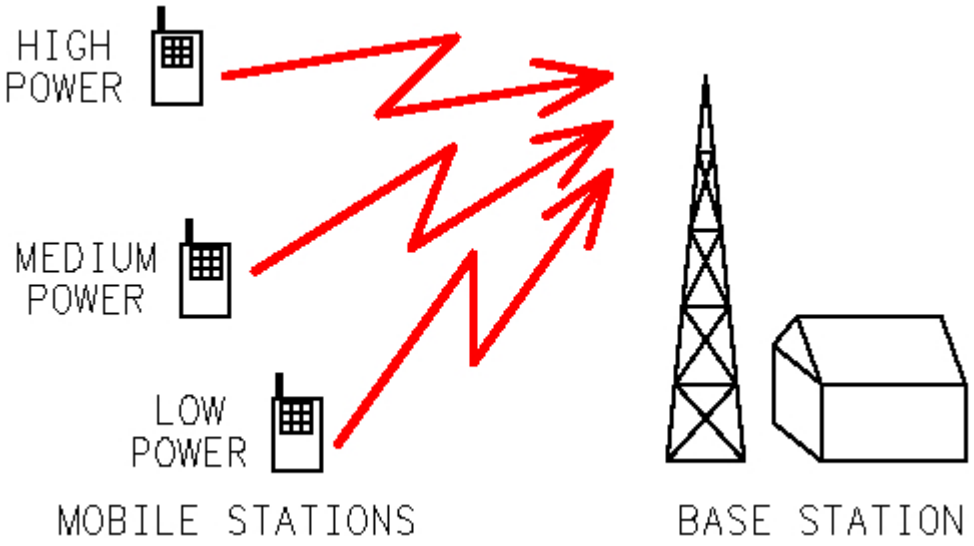


- Low amplitudes more likely
- Low average efficiency

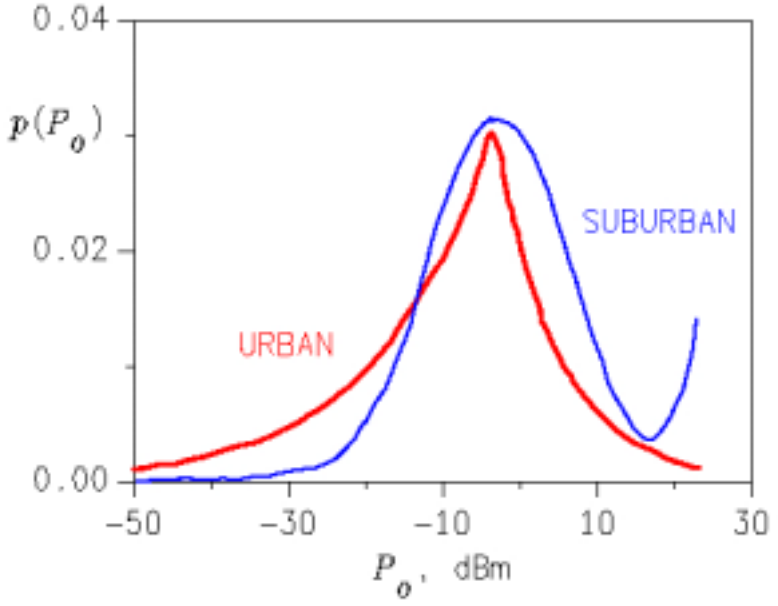
$$\eta_{AVG} = \frac{P_{oAVG}}{P_{iAVG}}$$

DYNAMIC POWER RANGE

MOBILE-BASE GEOMETRY



PDF OF PEP OUTPUT



- Use minimum power
- Wide range of PEP output

RF-POWER AMPLIFIERS

CONVENTIONAL

- CLASS A
- CLASS B
- CLASS C

HIGH EFFICIENCY

- CLASS D
- CLASS E
- CLASS F

EFFICIENCY

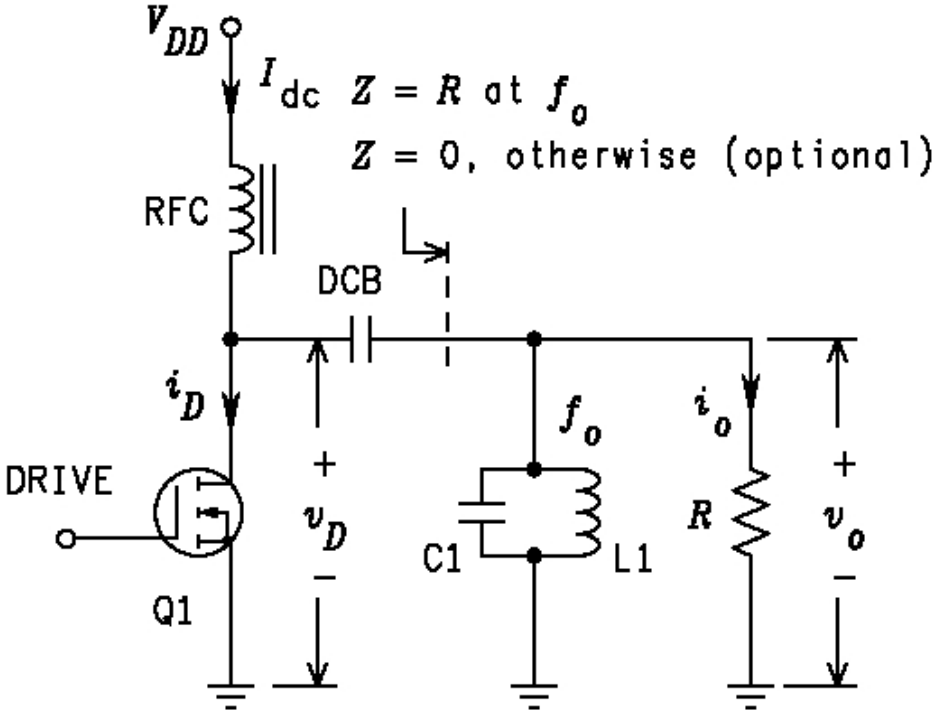
$$\eta = P_o / P_i$$

UTILIZATION FACTOR

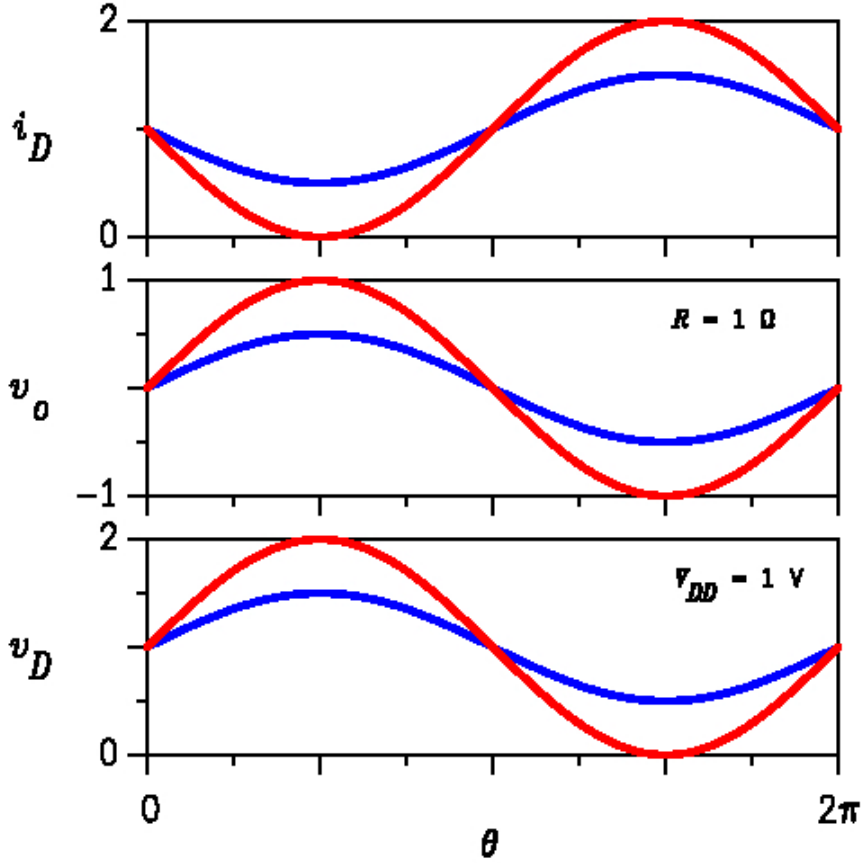
$$P_{max} = \frac{P_{omax}}{v_{Dmax}\, i_{Dmax}}$$

CLASS-A POWER AMPLIFIER

CIRCUIT



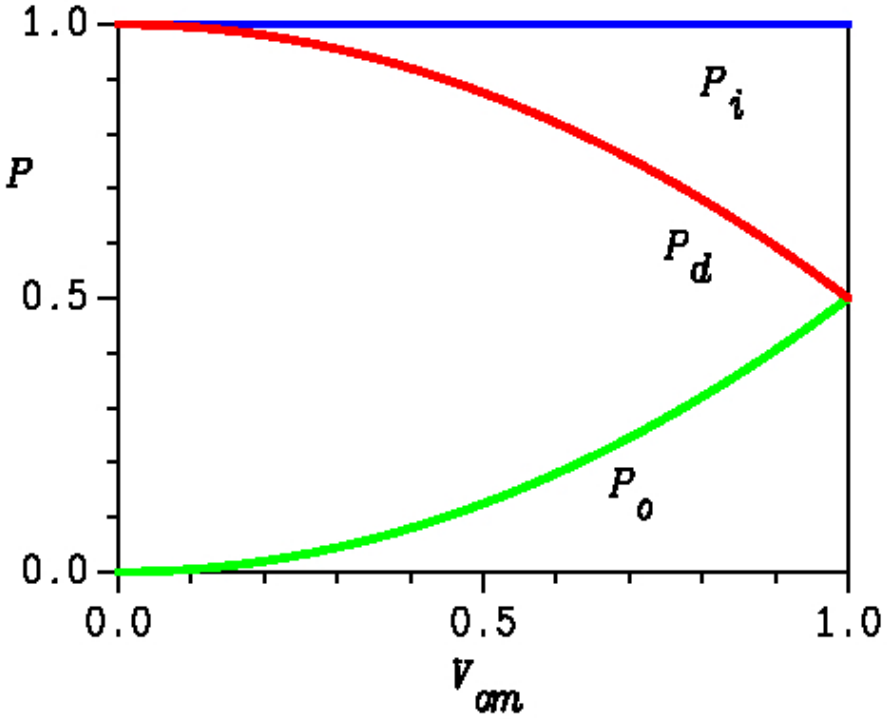
WAVEFORMS



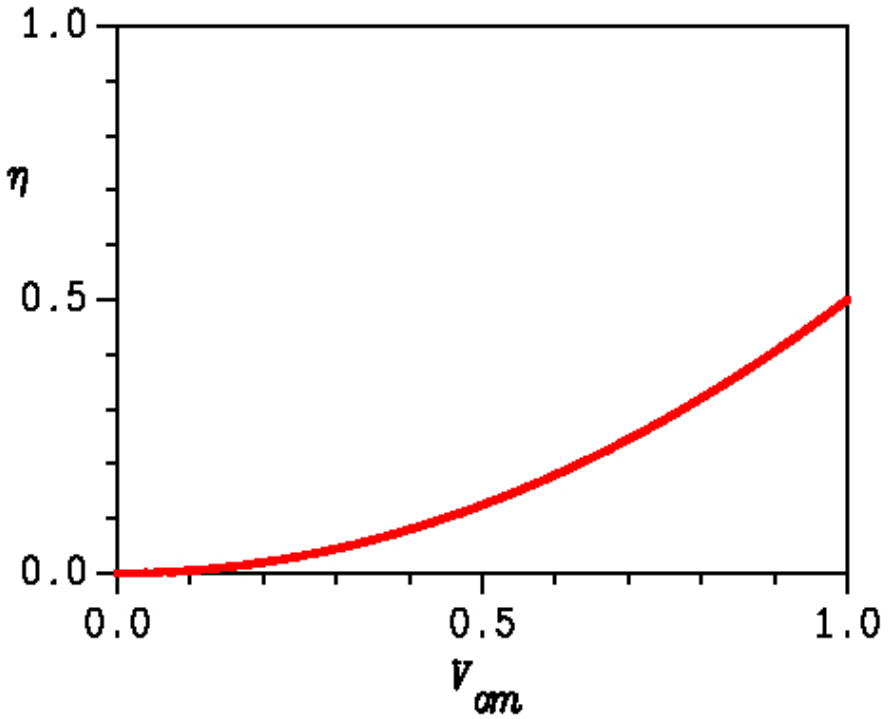
- $i_D > 0$ (360° conduction)
- No harmonics
- Output filter optional

CLASS A POWER AND EFFICIENCY

POWER



EFFICIENCY

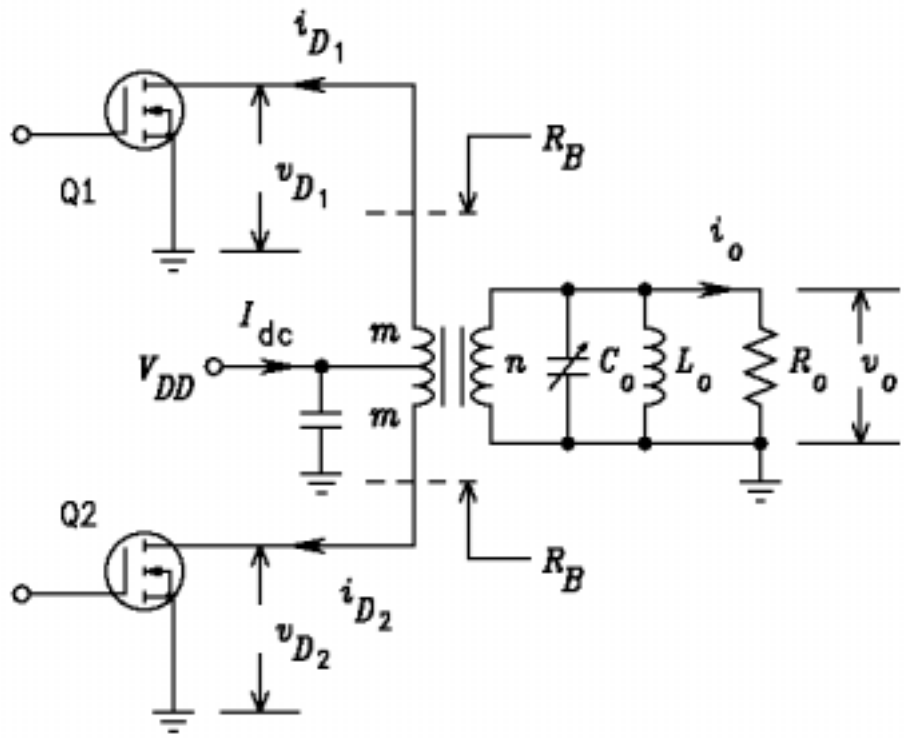


- Ideal transistors
- $V_{DD} = 1$, $R = 1$
- Efficiency ~ output power
- $\eta_{PEP} = 1/2 = 0.5$

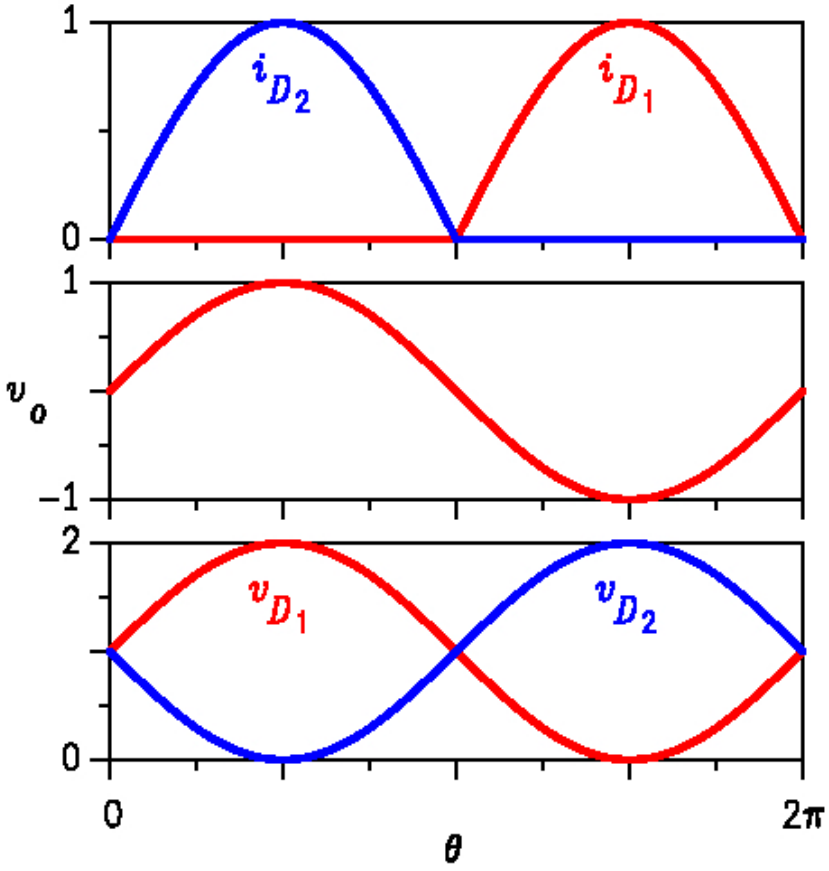
$$P_{max} = 0.125$$

CLASS-B POWER AMPLIFIER

CIRCUIT



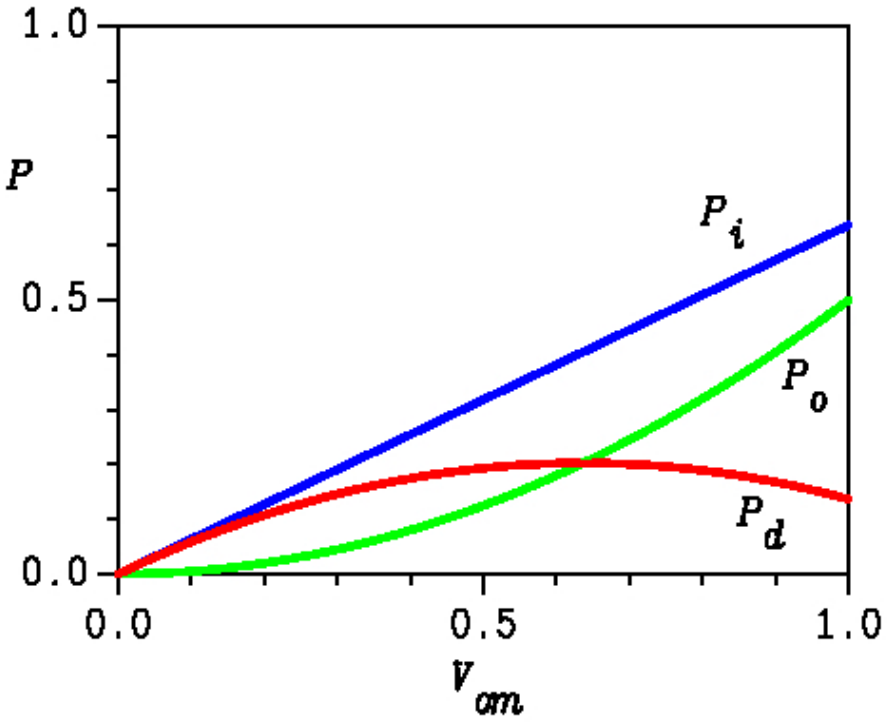
WAVEFORMS



- $R_B = (m/n)^2 R_o$
- Q1 and Q2 conduct alternately
- ≈ 180° conduction angle

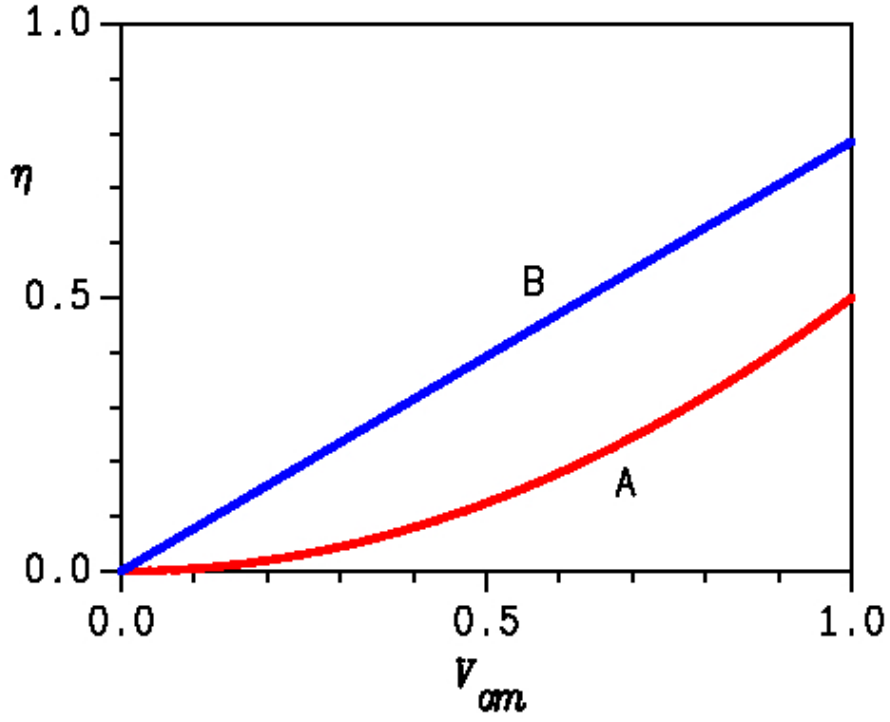
CLASS B POWER AND EFFICIENCY

POWER



- Ideal transistors
- $V_{DD} = 1$, $R = 1$

EFFICIENCY

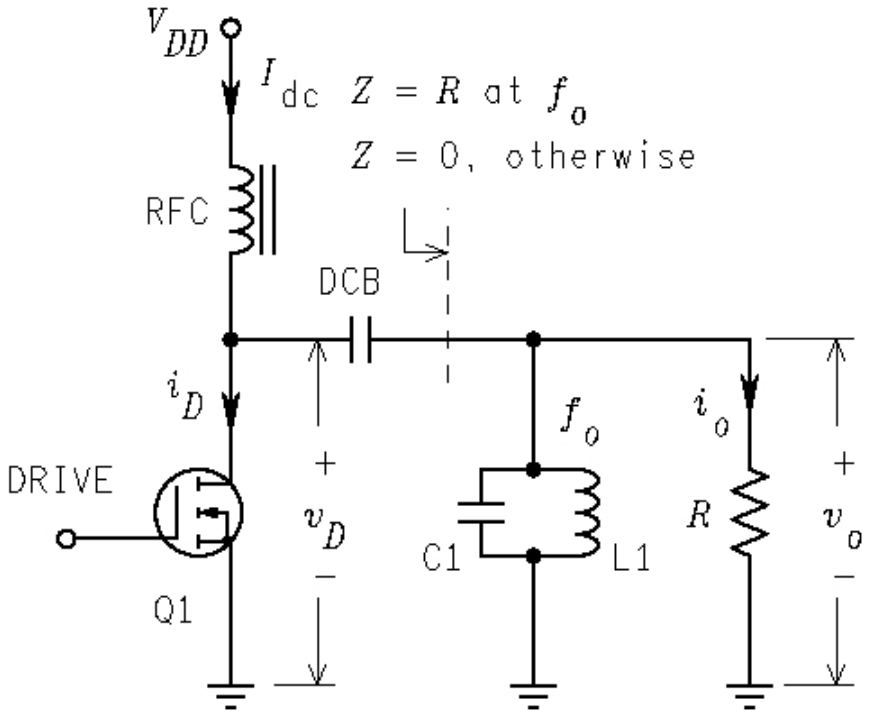


- Efficiency ~ output voltage
- $\eta_{PEP} = \pi/4 = 0.785$

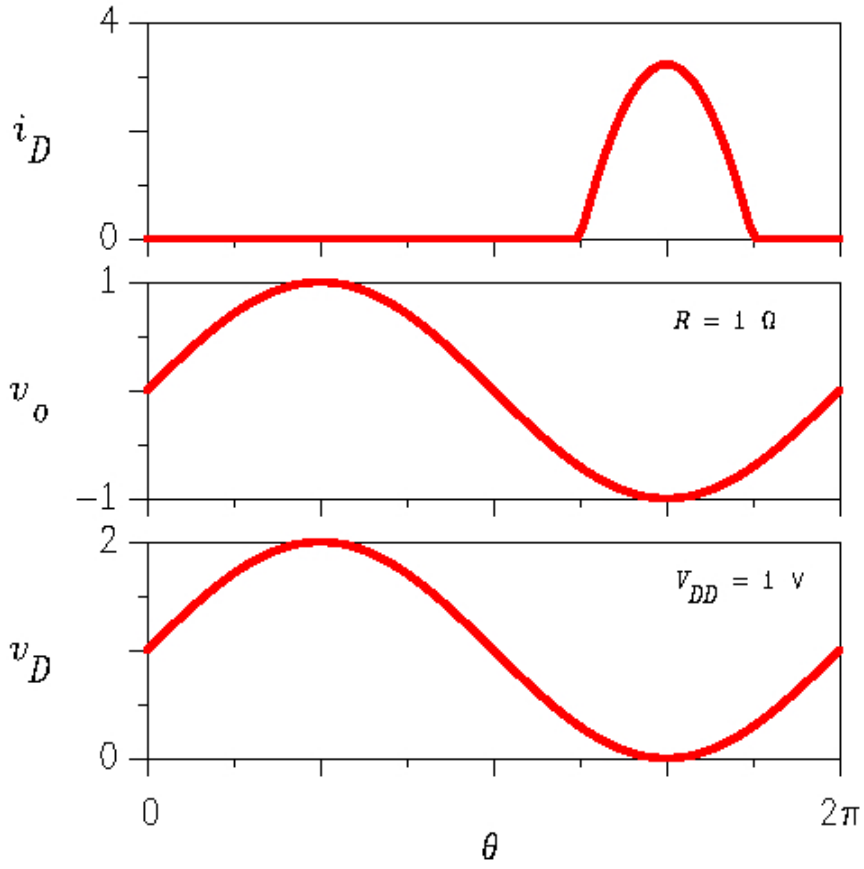
$$P_{max} = 0.25$$

CLASS-C POWER AMPLIFIER

CIRCUIT



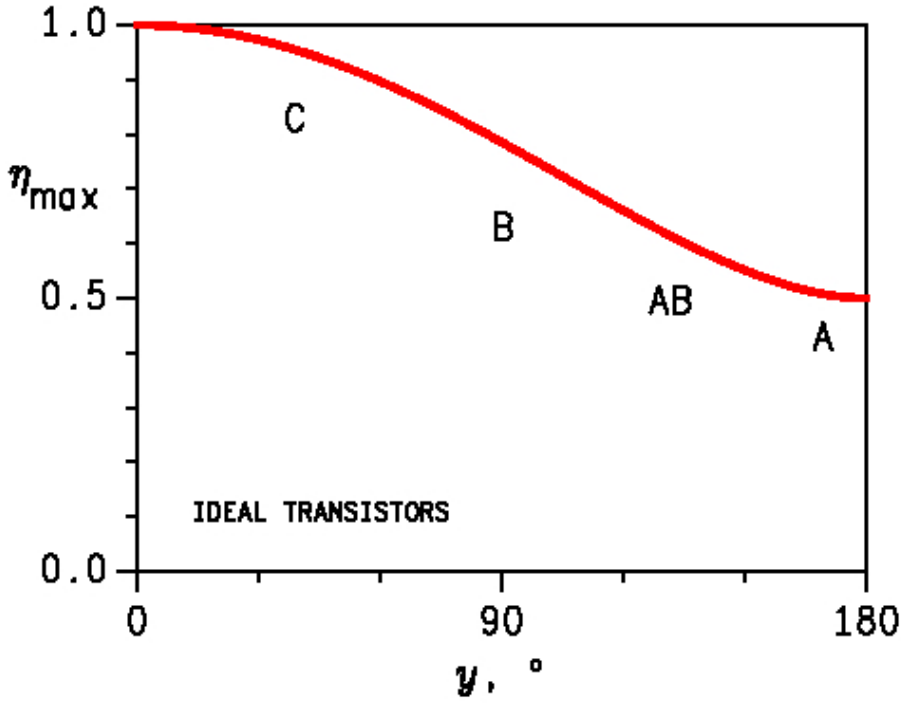
WAVEFORMS



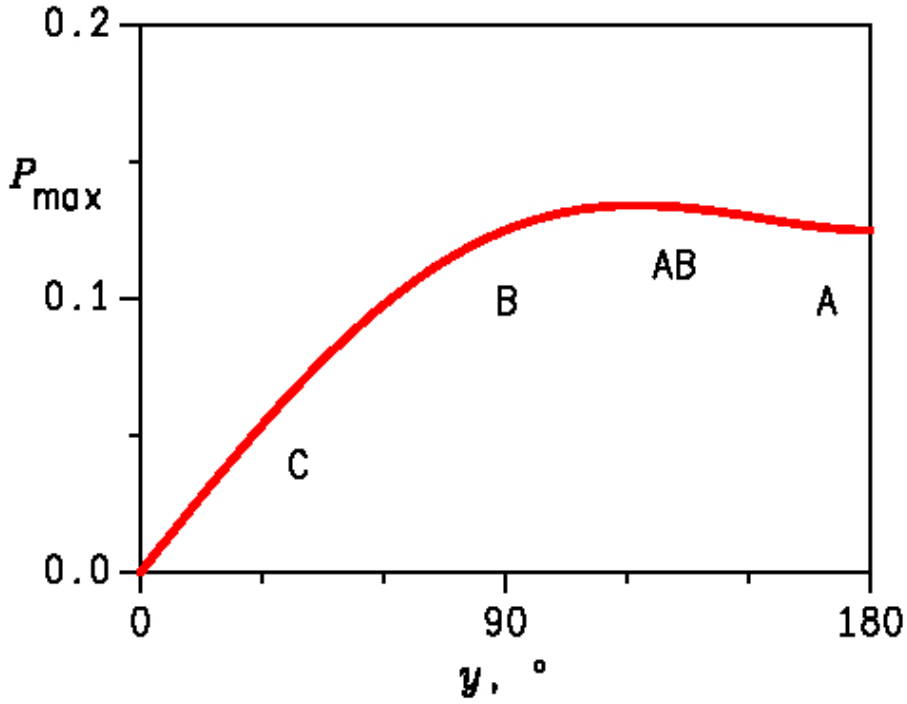
- Drain current < 180°
- Increased efficiency
- Inherent harmonics and nonlinearity

BIAS - CLASSES A, B, AND C

EFFICIENCY



POWER CAPABILITY



Gate bias controls conduction angle

360°: Class A - linear

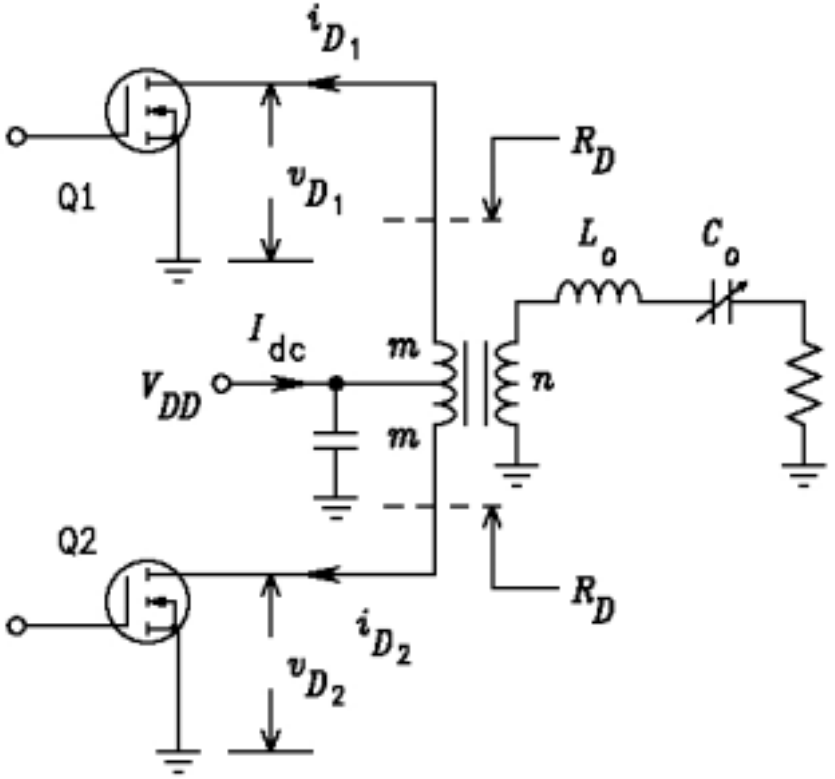
245°: Class AB - maximum power

180°: Class B - linear

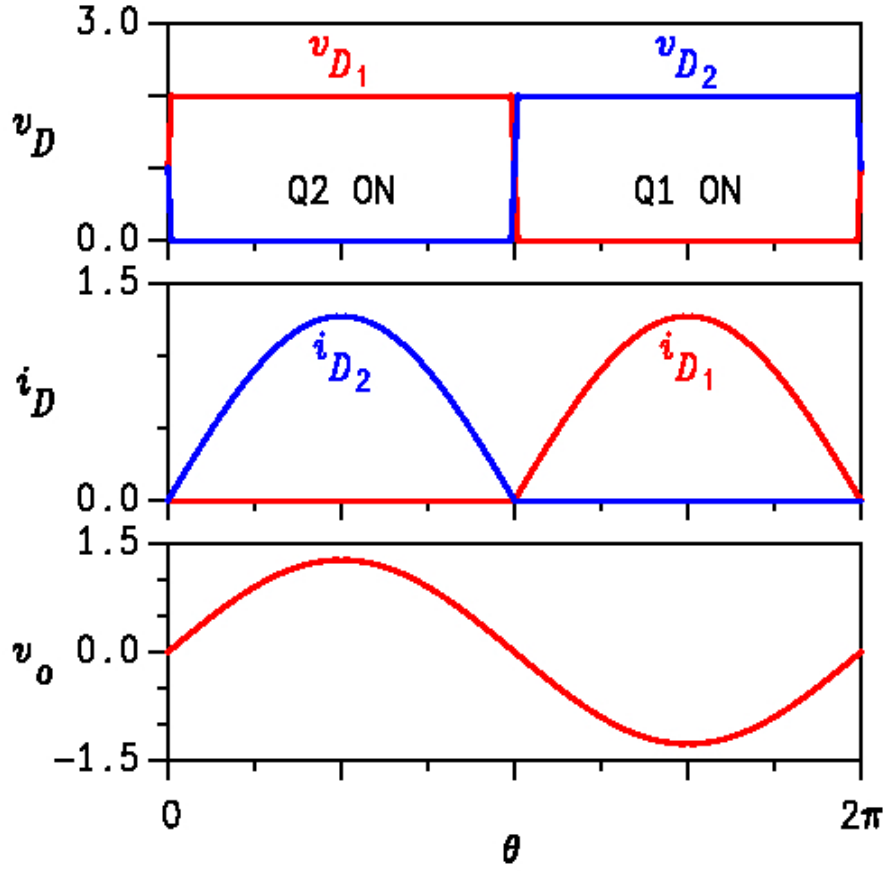
<180°: Class C

CLASS-D POWER AMPLIFIER

CIRCUIT



WAVEFORMS

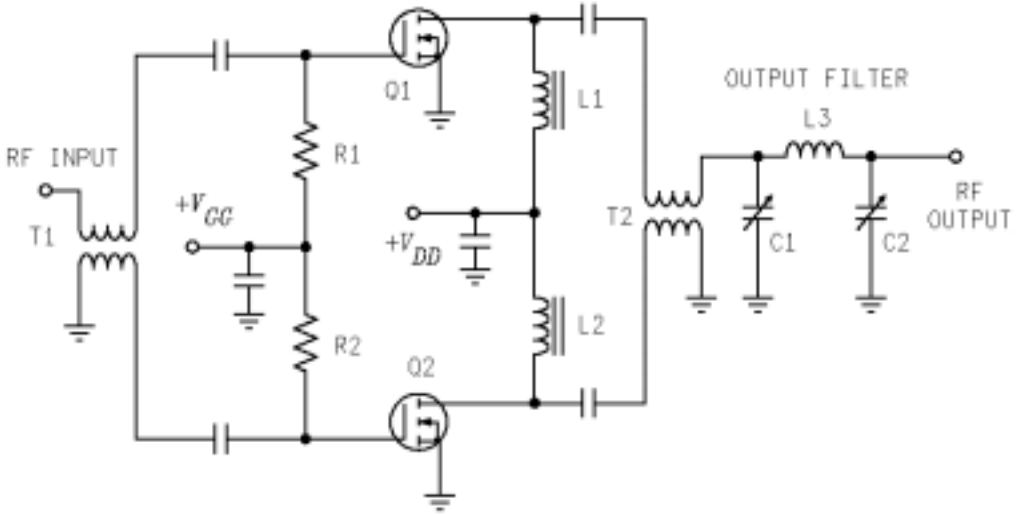


- $R_D = (m/n)^2 R_o$
- Q1 and Q2 on/off alternately
- ≈ 180° conduction angle

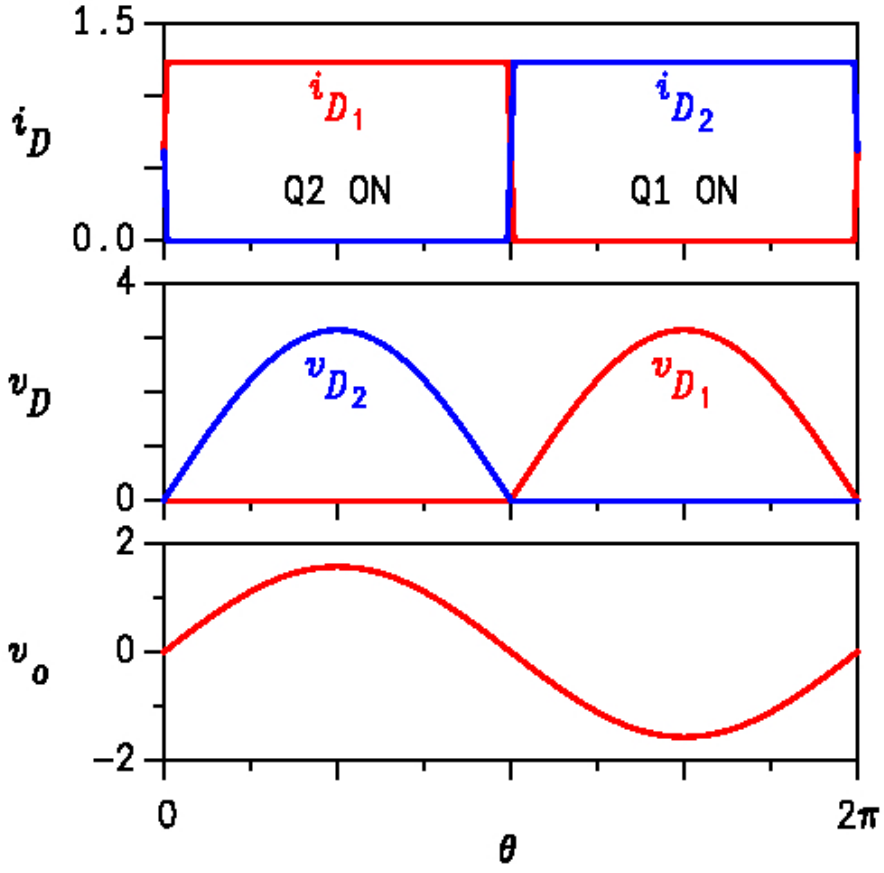
$\eta = 1 \quad P_{max} = 0.318$

CLASS D - CURRENT SWITCHING

CIRCUIT



WAVEFORMS



- $R_D = (m/n)^2 R_o$
- Q1 and Q2 on/off alternately
- ≈ 180° conduction angle

$\eta = 1 \quad P_{max} = 0.318$

CLASS D - CHARACTERISTICS

LOSSES

- On-state resistance
- Switching time
- Drain capacitance

TYPICAL USES

- Voltage switching: LF/MF/HF PAs
- Current switching: 1 GHz

ADVANTAGES

- Maximum power for FET ratings
- Easy to tune

DISADVANTAGES

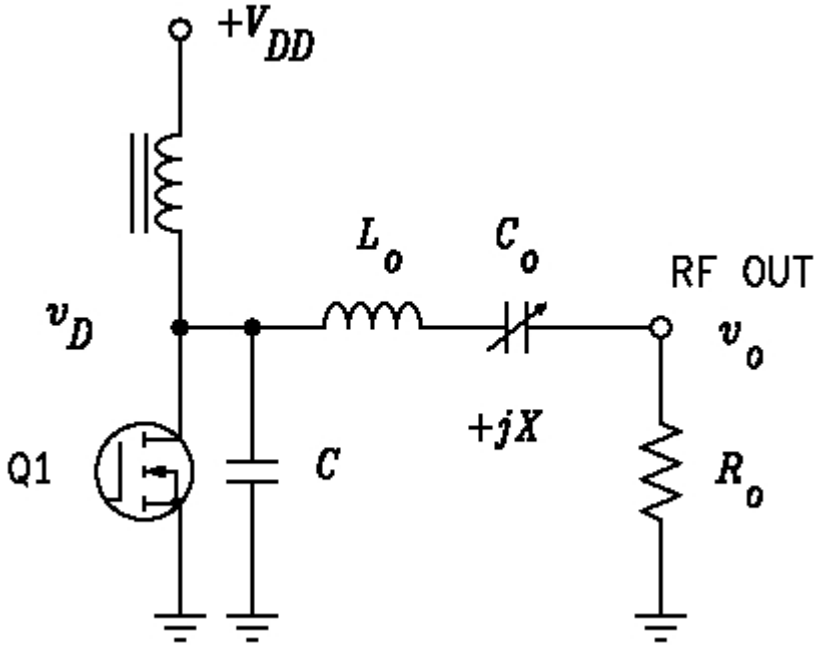
- Capacitive loss increases with frequency
- Timing errors create short circuit
- Soft drive usually needed

CLASS D - PROTOTYPES

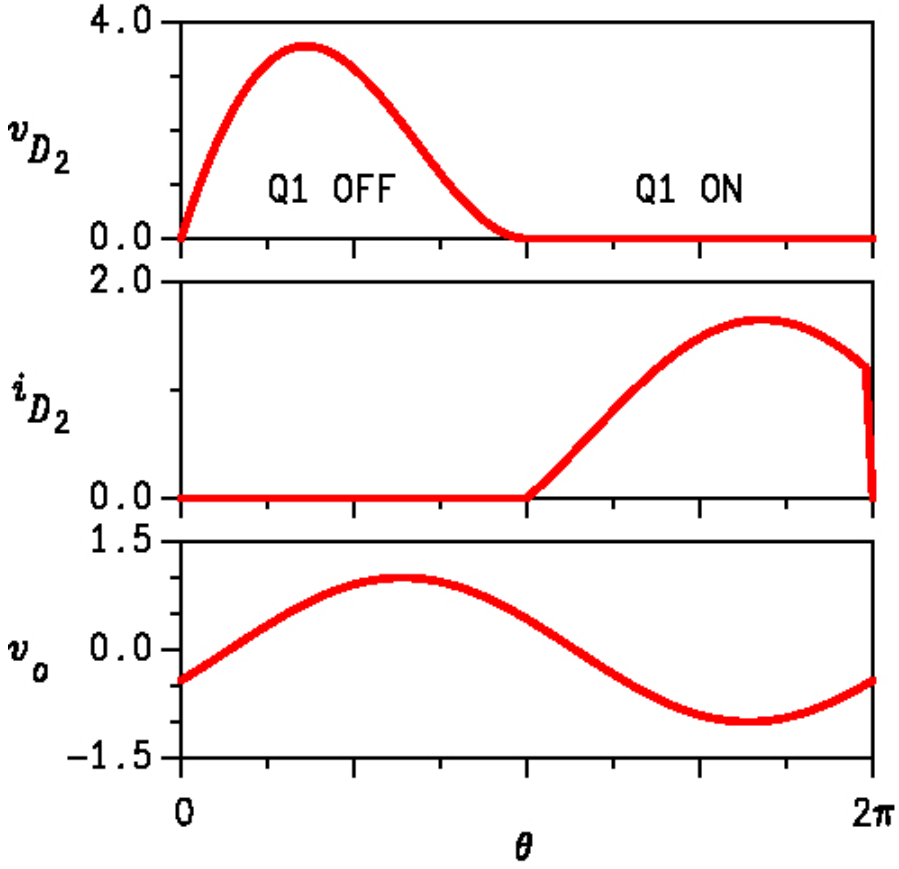
HF	VHF/UHF
VMOS FETs	GaN HEMTs
1.8 - 30 MHz	25 - 400 MHz
300 - 400 W	70 - 100 W
70 - 80%	60 - 70%

CLASS-E POWER AMPLIFIER

CIRCUIT



WAVEFORMS



- Transistor = switch
- Dynamics → waveform
- Discharge C_{DS}
- $\eta = 1$

$$P_{max} = 0.098$$

CLASS E - CHARACTERISTICS

LOSSES

- On-state resistance
- Switching time

TYPICAL USES

- VHF/UHF PAs (true transient class E)
- HF PAs using "low-cost" MOSFETs
- Microwave PAs
  (transmission-line approximations)

ADVANTAGES

- No loss from drain capacitance
- No short from timing error

DISADVANTAGES

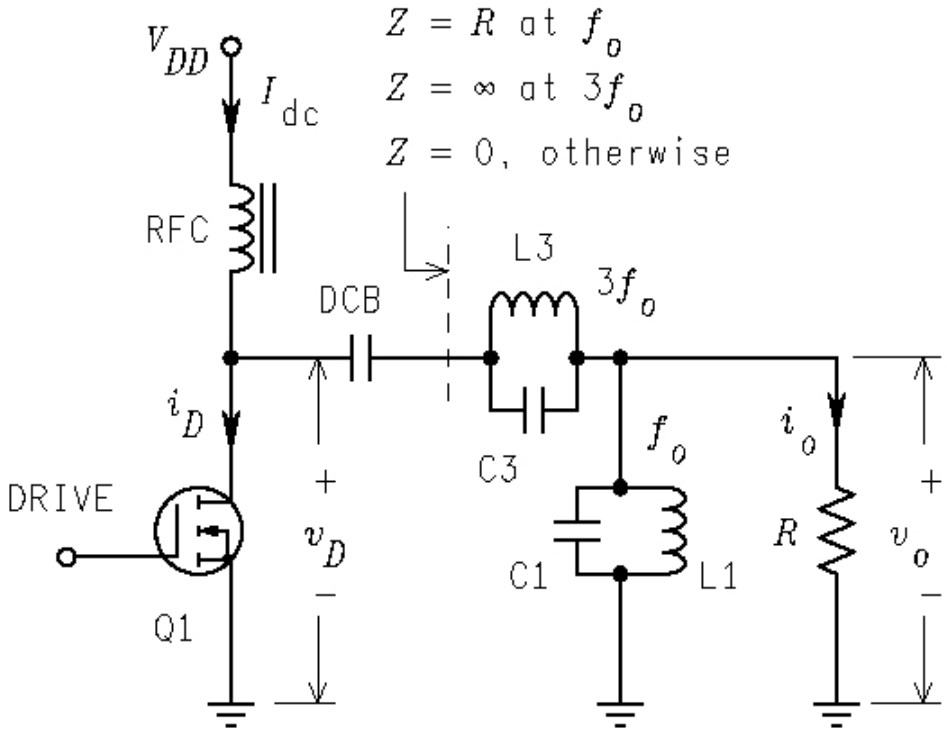
- Lower output than class D
- Higher loss from R_{on}

CLASS E - PROTOTYPES

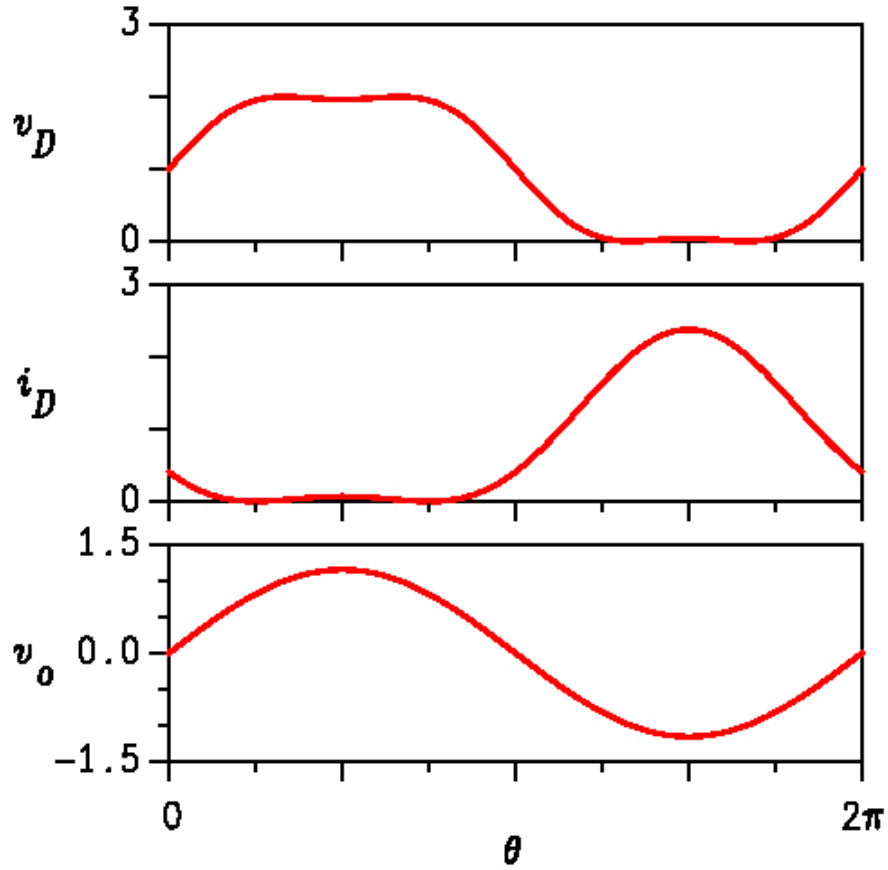
HF/VHF	VHF/UHF
VMOS FET	LDMOS FET
1.8 - 128 MHz	25 - 400 MHz
200 W	60 - 78 W
70 - 90%	60 - 80%

CLASS-F POWER AMPLIFIER

CIRCUIT



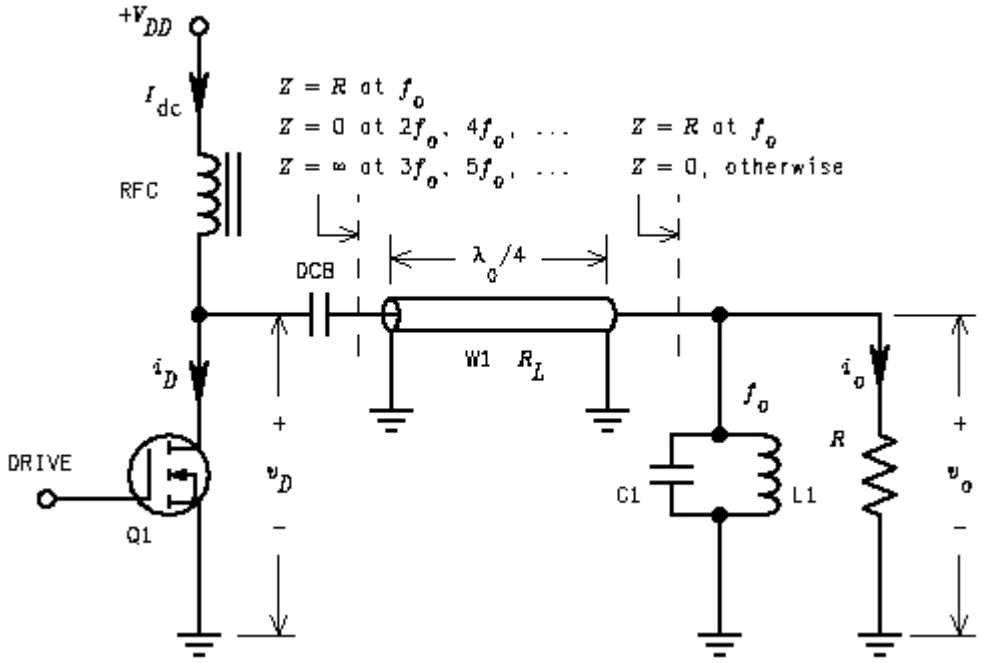
WAVEFORMS



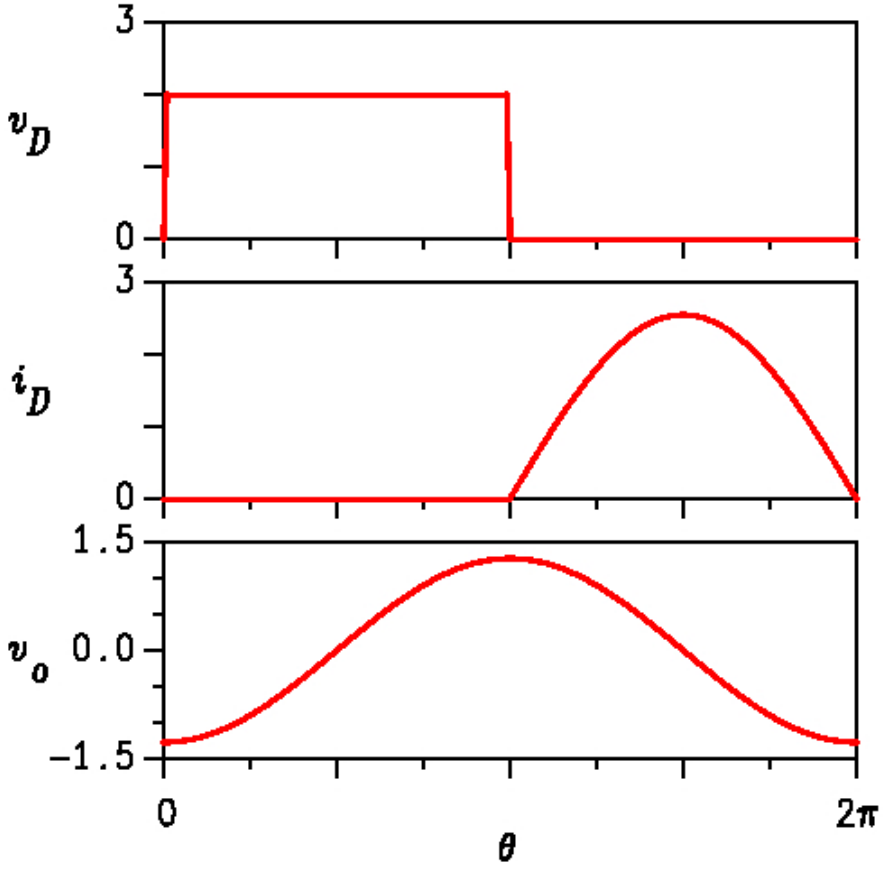
- Voltage ≈ square wave
- Current ≈ half sine wave
- Power and efficiency increased

CLASS-F - ALL HARMONICS

CIRCUIT



WAVEFORMS

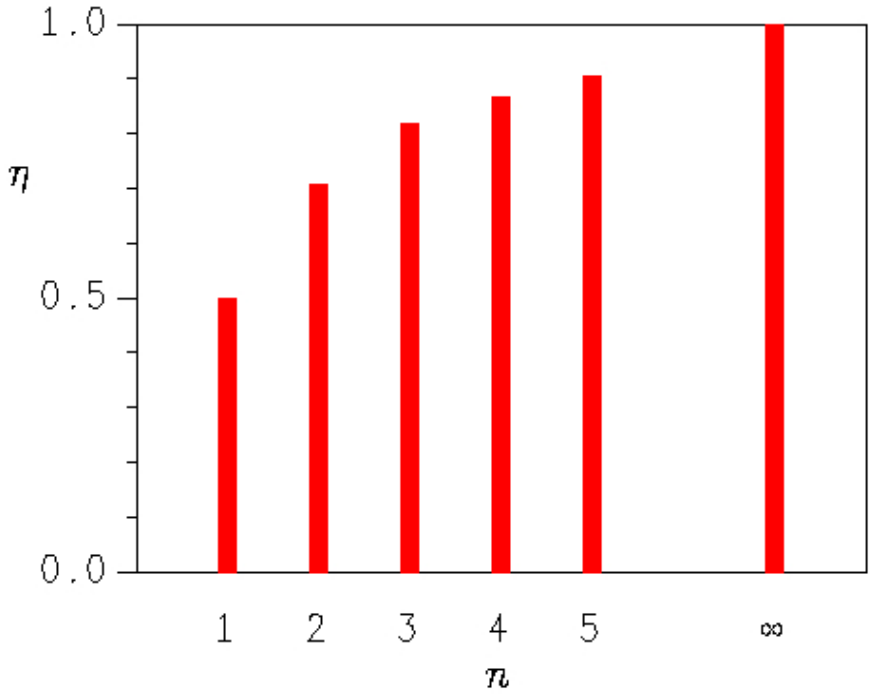


- Quarter-wavelength T line
- Voltage = square wave
- Current = half sine wave
- Half of class-D PA

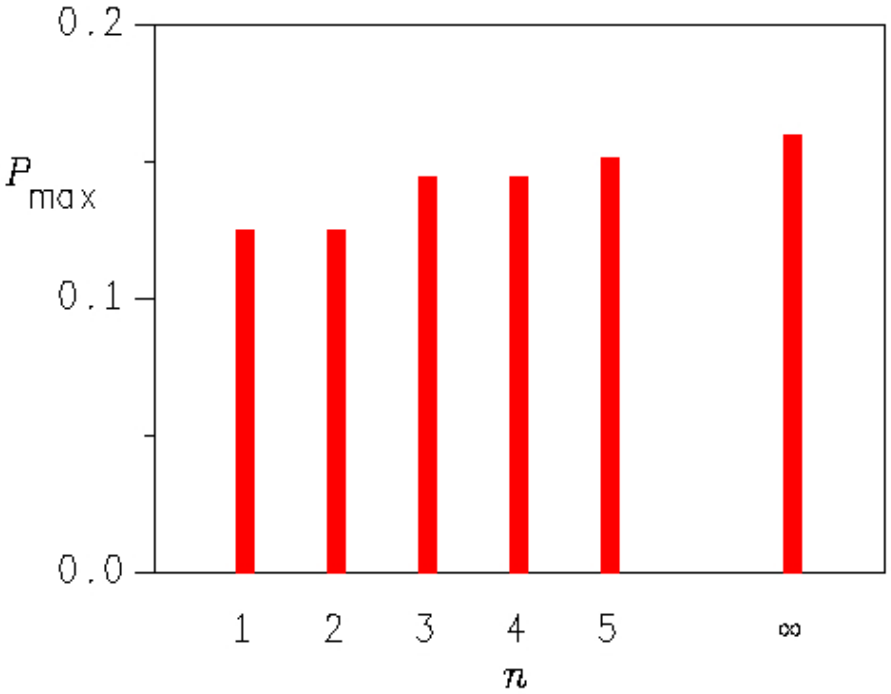
$\eta = 1 \qquad P_{max} = 0.159$

CLASS-F - CHARACTERISTICS

EFFICIENCY

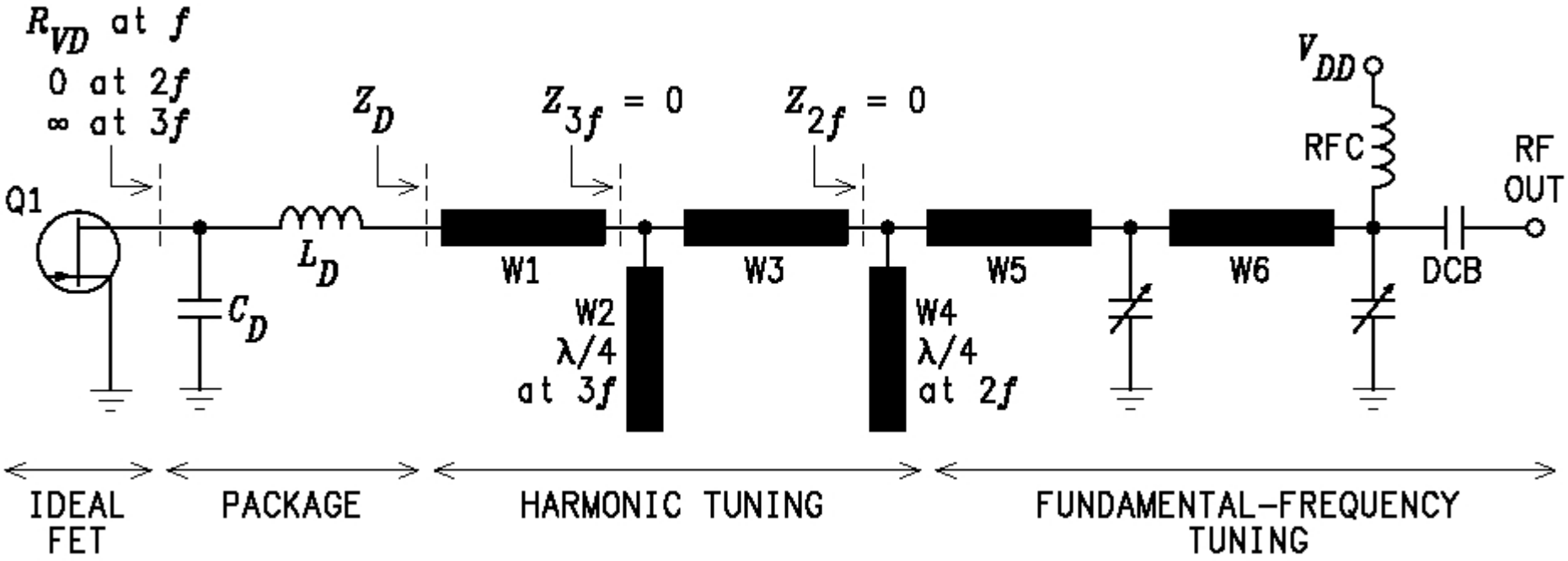


POWER OUTPUT



- Efficiency and output increase with number of controlled harmonics
- Progressively smaller increases
- Evens and odds affect efficiency
- Odds affect output
- Can (must) tune-out drain capacitance
- Transmission-line resonators
- Good for UHF, microwave

CLASS-F – MICROWAVE

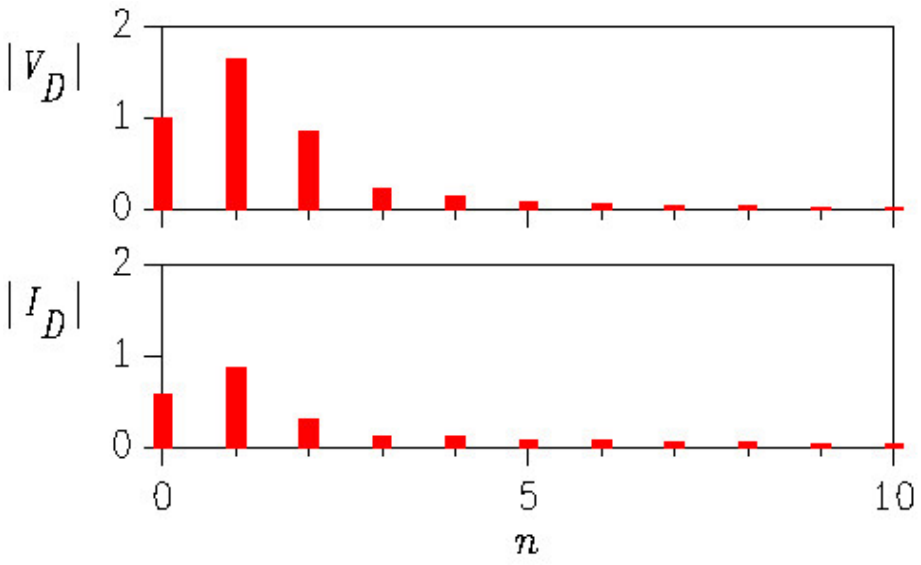
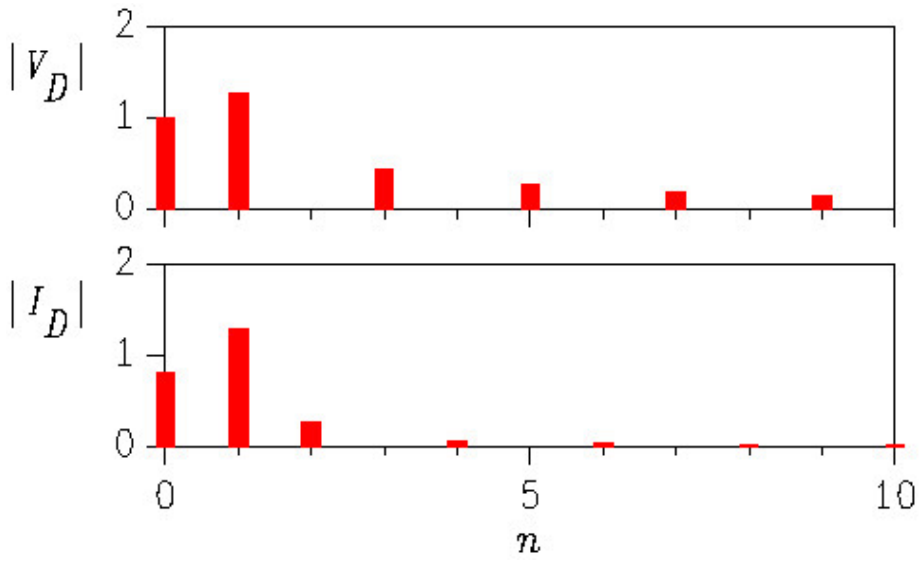


- Virtual drain of ideal FET sees ideal impedances
- 3*f* and 2*f* shorts by λ/4 lines
- 3*f* short transforms through W1 and package to virtual drain
- Circuit to right does not affect 3*f*
- 2*f* short transforms through W3, W2, W1, package to virtual drain
- Circuit to right does not affect 2*f*
- Remaining components match fundamental

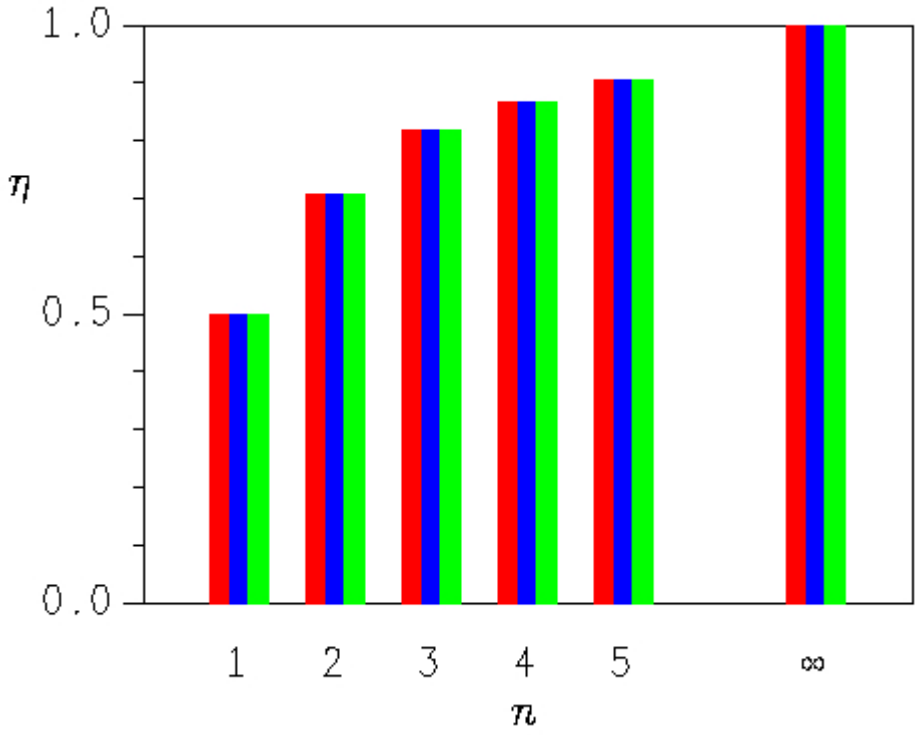
CLASS F - PROTOTYPES

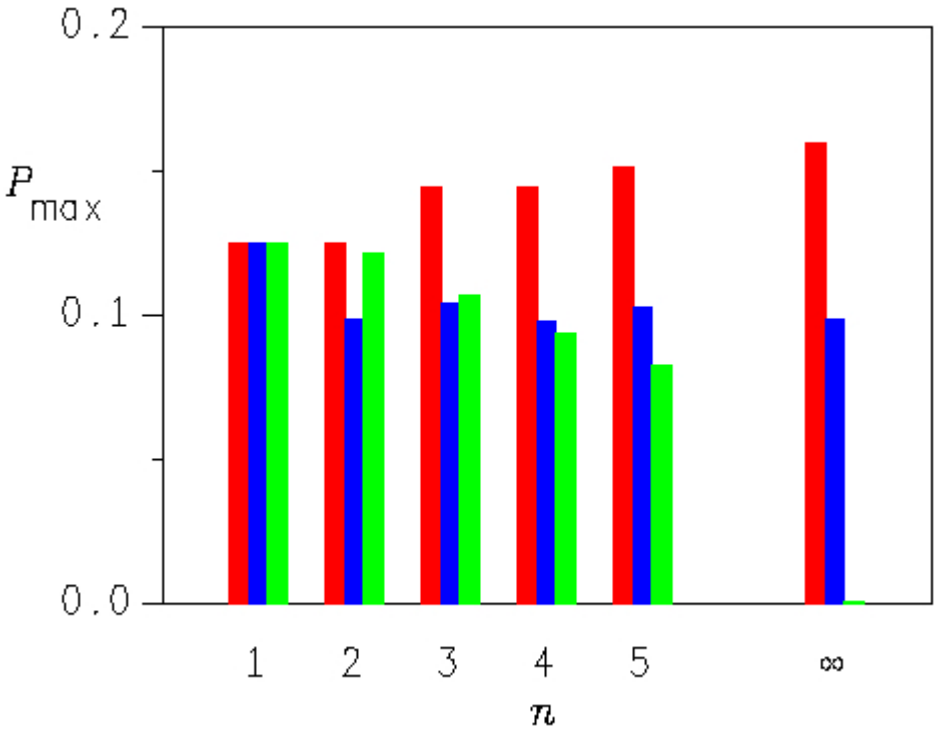
500 MHz	1.2 GHz
GaN HEMT	GaN HEMT
54 W	55 W
71%	74%

MICROWAVE CLASS E vs. CLASS F

CLASS E	CLASS F
	
FUNDAMENTAL	
$R + jX$ ($\approx 45°$)	R
HARMONICS	
V and I: Nonzero	$V > 0$, $I = 0$ or
90°	$V = 0$, $I > 0$
No power	No power

CLASS C, E, AND F - FINITE HARMONICS





Depends upon *n*

Independent of class

Highest for F

Class C: Decreases with *n*

REAL UHF/MICROWAVE HEPAS

REALITY

- FET not ideal switch
- FET not ideal current source
- Varactor drain capacitance
- Harmonics happen

CLASS EF

- T-line network like class F
- Resonators control *2f* and *3f*
- Drain capacitance for higher *f*
- Soft switching
- Small inductive reactance at *f*
- Power output of class F
- Efficiency of class E

TRANSMISSION-LINE CLASS E

- Finite-harmonic approximation
- T-line network like class F
- *f*: $R + jX$ ($\approx 45°$)
- 2*f*: ≈ ideal
- Both v_D and i_D have *f* and *2f*

CLASS J

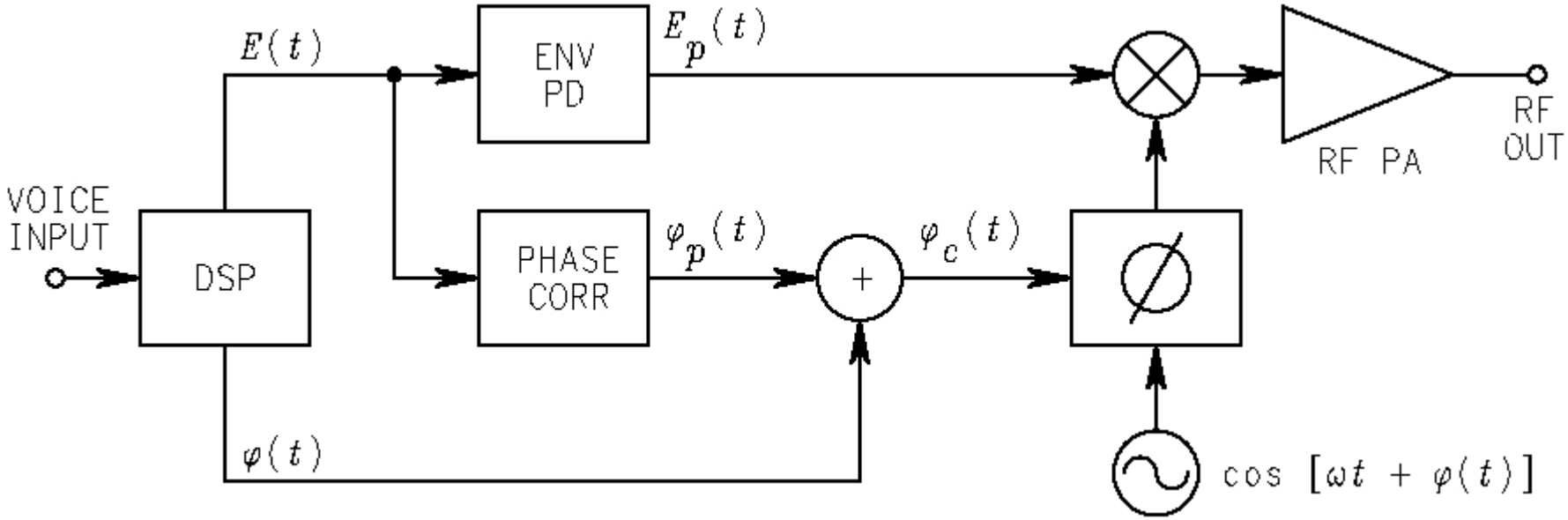
- Cripps terminology
- v_D: 2 harmonics
- i_D: Half sine wave
- *f*: $R + jX$ ($\approx 45°$)
- *nf*: Drain capacitance
- $\eta = 0.785$
- $P_{max} = 0.0858$

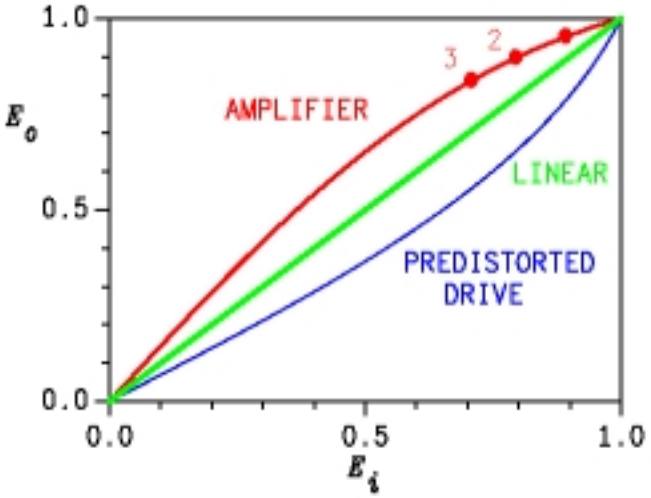
ARCHITECTURES - TWO CATEGORIES

1. HIGH EFFICIENCY OVER MODULATION ENVELOPE

2. HIGH EFFICIENCY OVER DYNAMIC RANGE

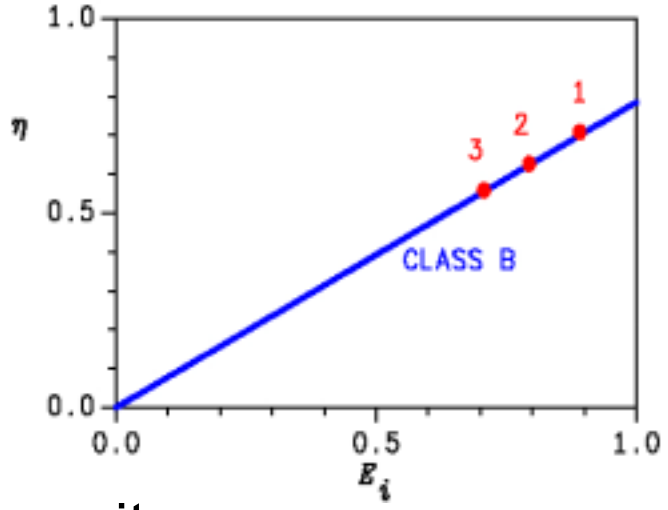
PREDISTORTION





Nonlinearity

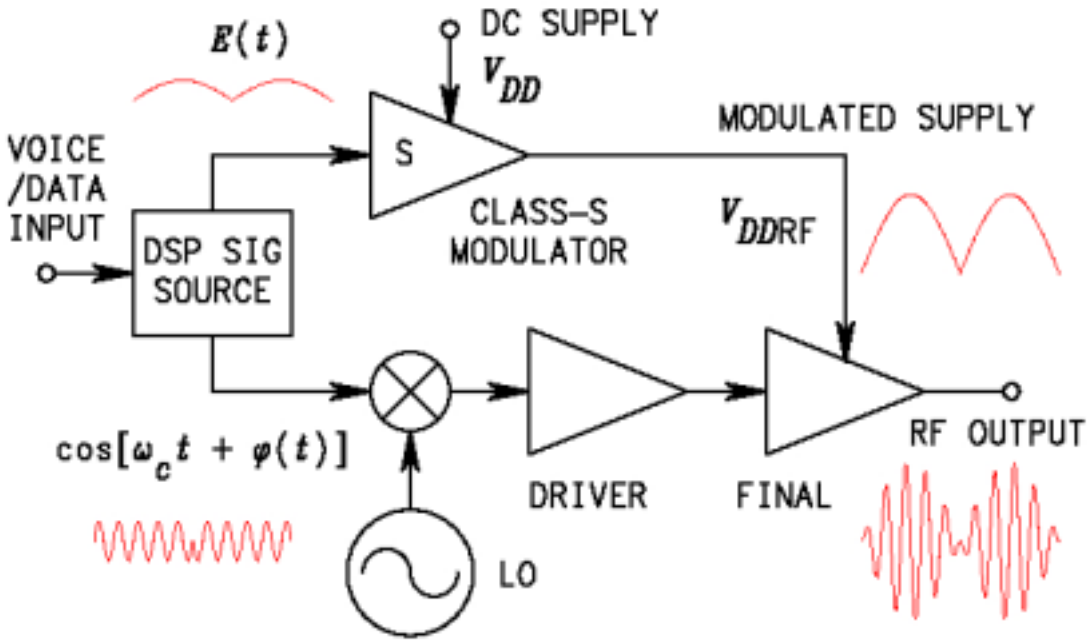
- Backoff
- Reduced η

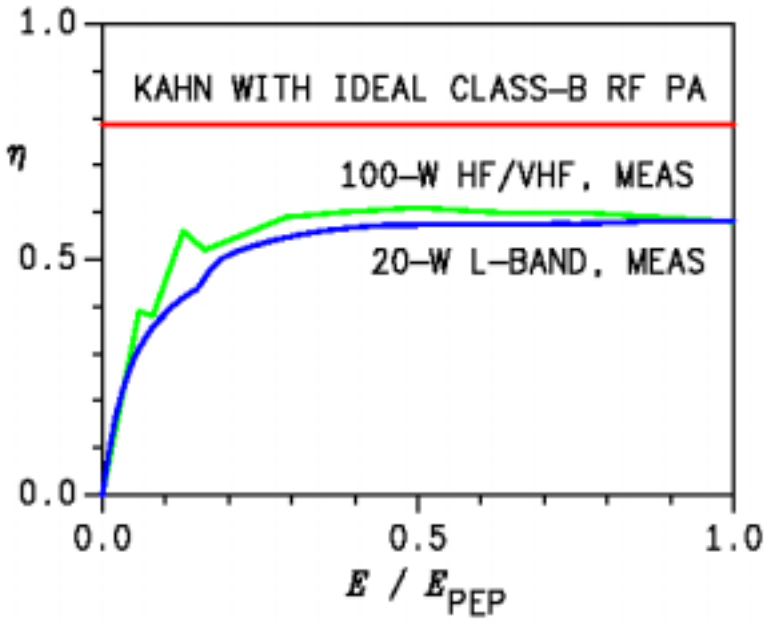


Predistortion

- Eliminates nonlinearity
- PEP efficiency

KAHN TECHNIQUE

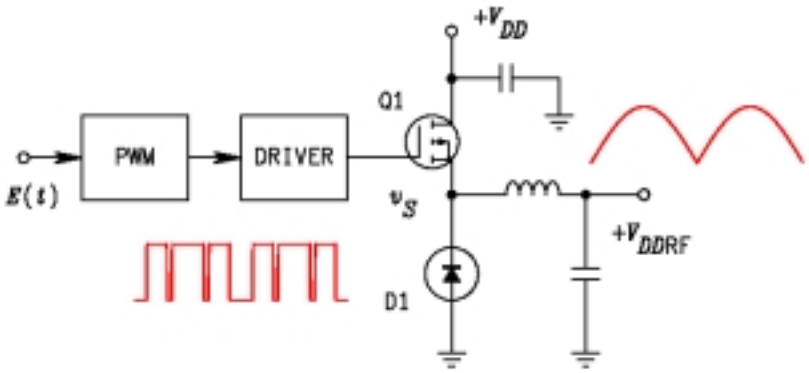




- High-efficiency linear transmitter
- RF signal: Simultaneous AM, ΦM
- Saturated RF PA
- High-level AM
- Average efficiency 3 to 5 times class B

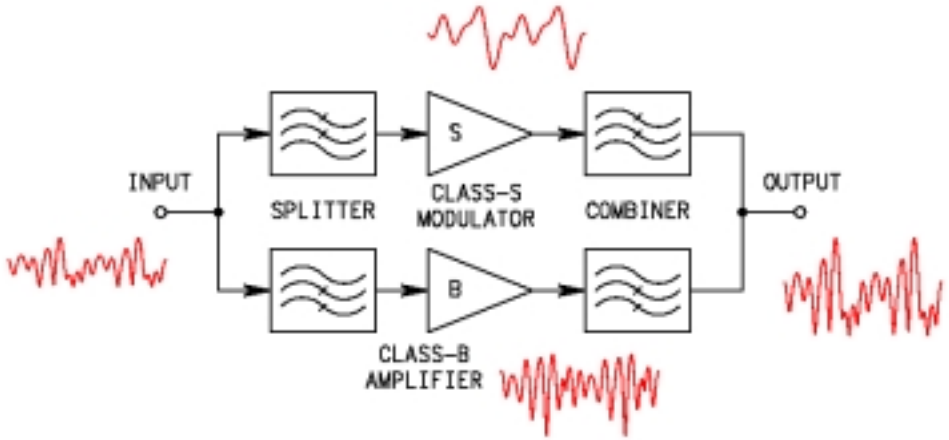
MODULATORS FOR KAHN TECHNIQUE

CLASS S



- Q1-D1 = SPDT switch
- Efficiency > 90%
- Wide dynamic range
- f_s > 6-7 B_{RF}

SPLIT BAND



LF COMPONENTS

- Most of power
- Amplify efficiently – class S

HF COMPONENTS

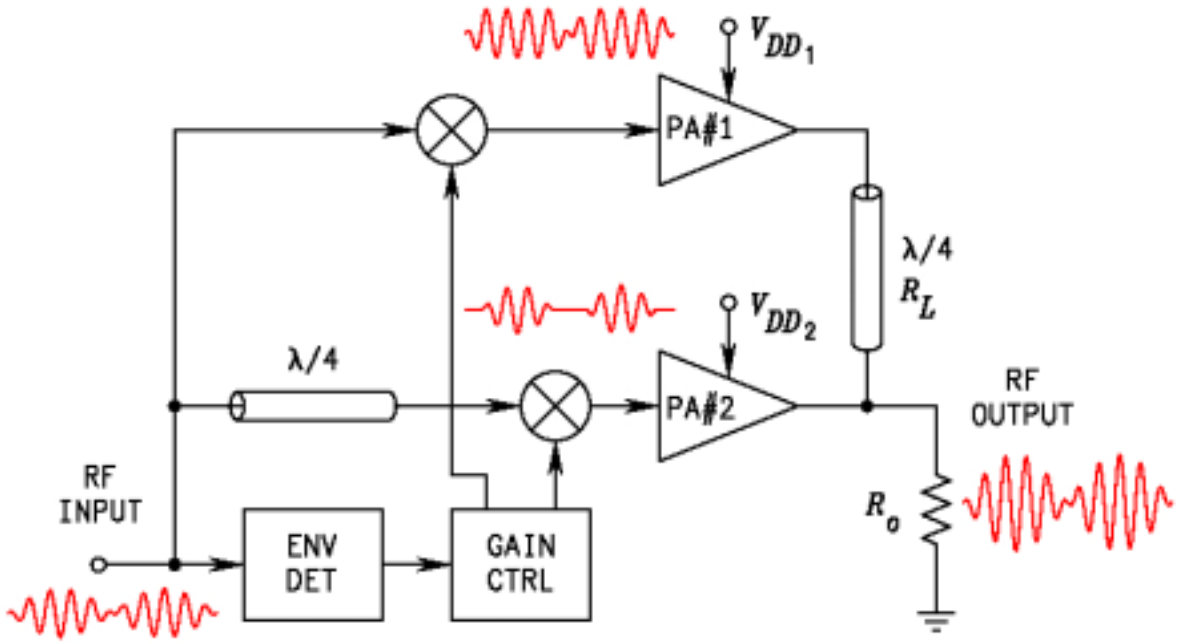
- Amplify linearly – class B

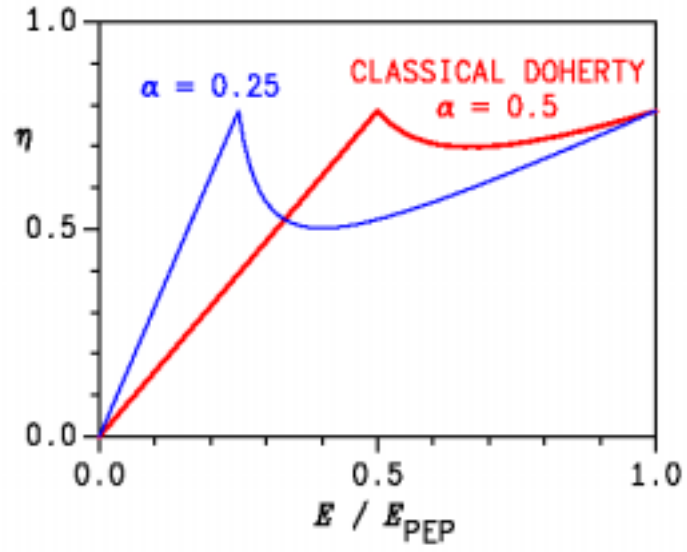
U.S. patent 6,252,634

PROTOTYPE KAHN TRANSMITTERS

HF-VHF	L BAND
MRI	Radar
10 - 128 MHz	1.2 GHz
500-kHz bandwidth	500-kHz bandwidth
Predistortion	Predistortion
200 W PEP	50 W PEP
70-80%	60%
2x average efficiency	2x average efficiency

DOHERTY TRANSMITTER





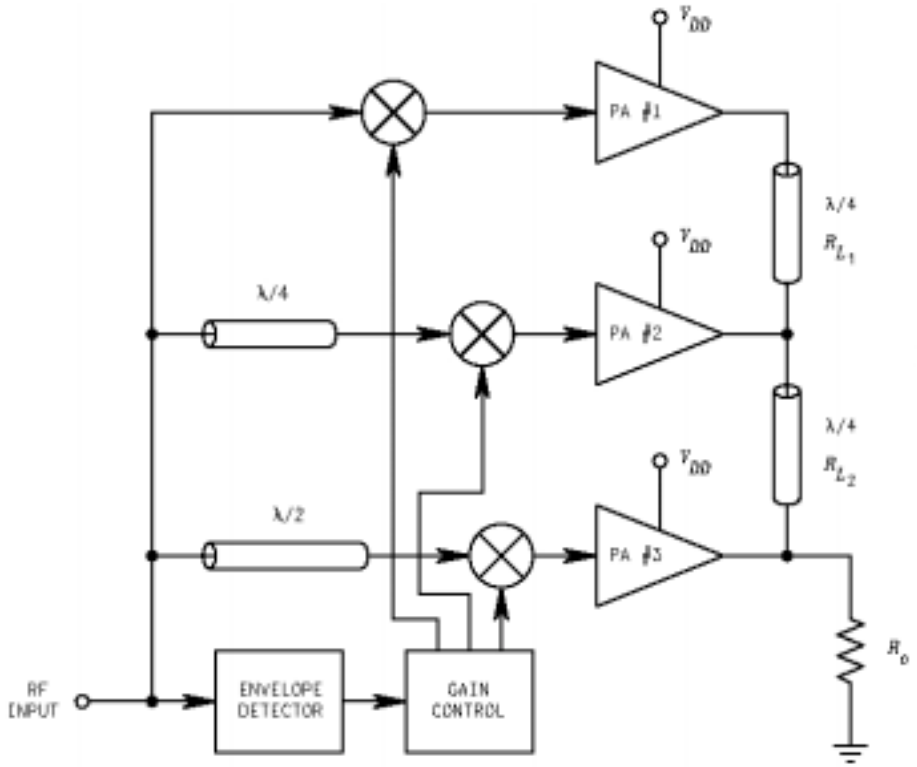
LOW AMPLITUDES

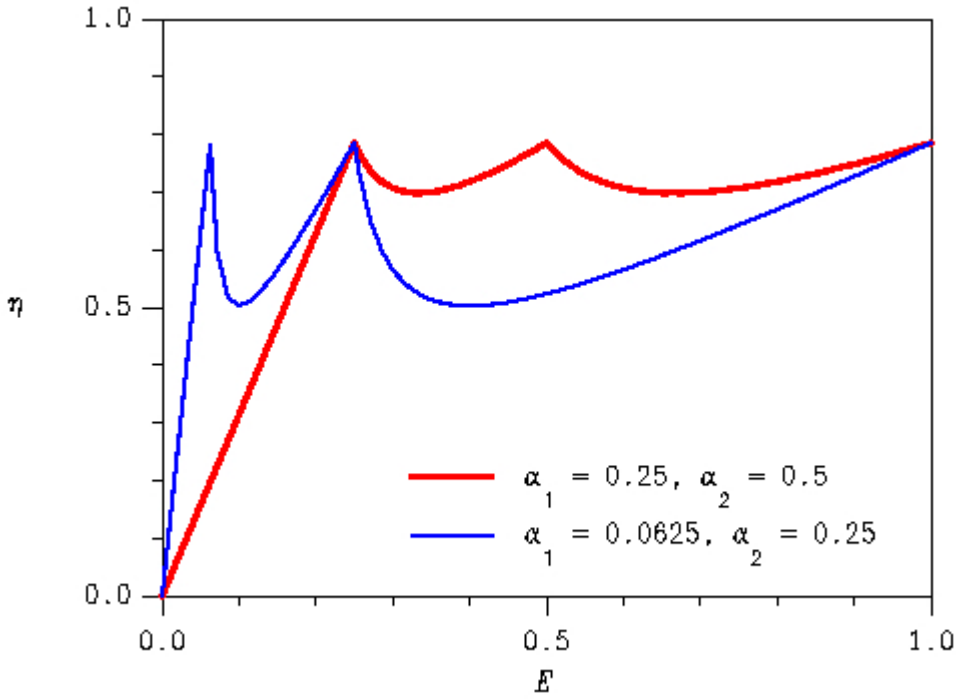
- PA #1 linear
- PA #2 off

HIGH AMPLITUDES

- PA #2 active
- PA #1 saturated variable load

THREE-STAGE DOHERTY





PRINCIPLES

PA1+PA2 = 2-S Doherty at low power

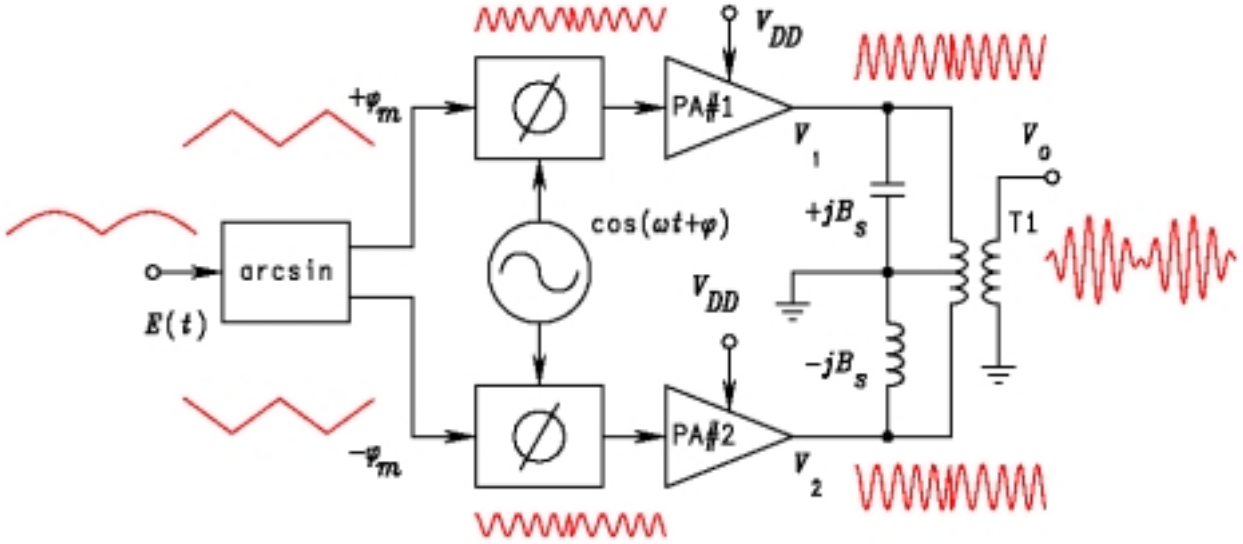
PA1+PA2 = carrier amp at high power

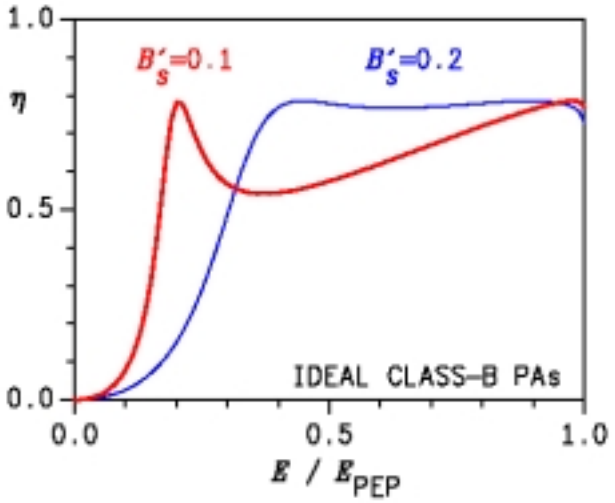
Good efficiency over wide range

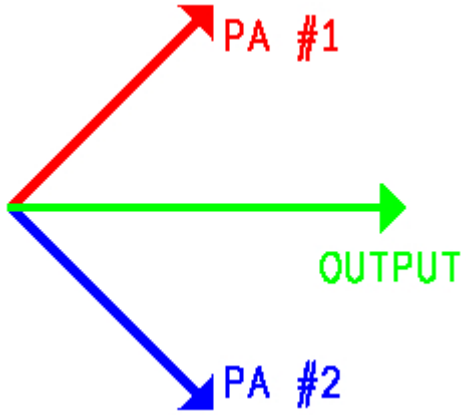
AVERAGE EFFICIENCY 10-dB P/A

Class B	28.0 %
2-S Doherty	60.0 %
3-S Doherty	70.0 %

CHIREIX OUTPHASING

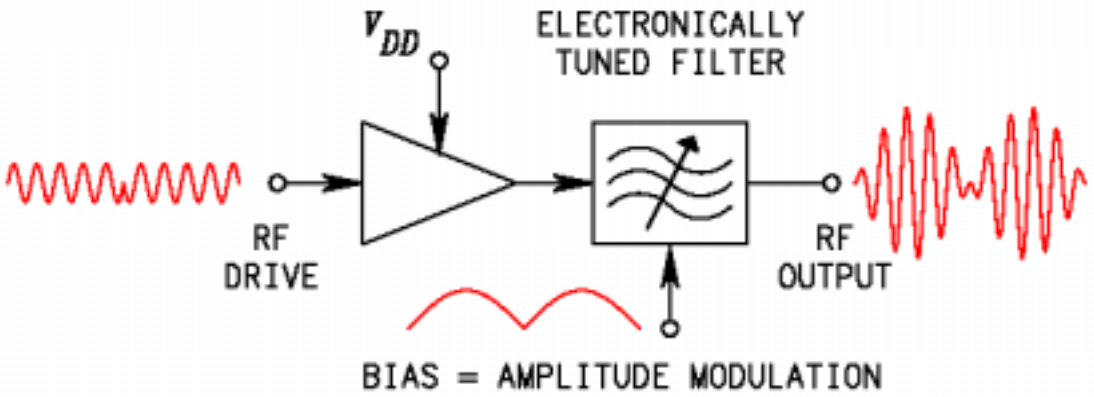


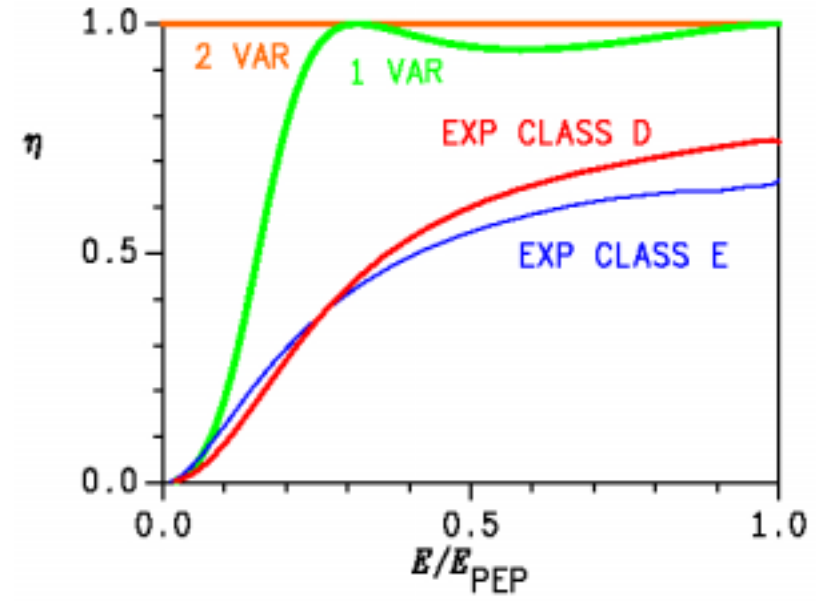




- Vary phases in opposite directions
- PAs saturated
- Sum -> desired amplitude
- Tune-out load reactance mid range
- Wide bandwidth - limited by phase modulator

LOAD MODULATION

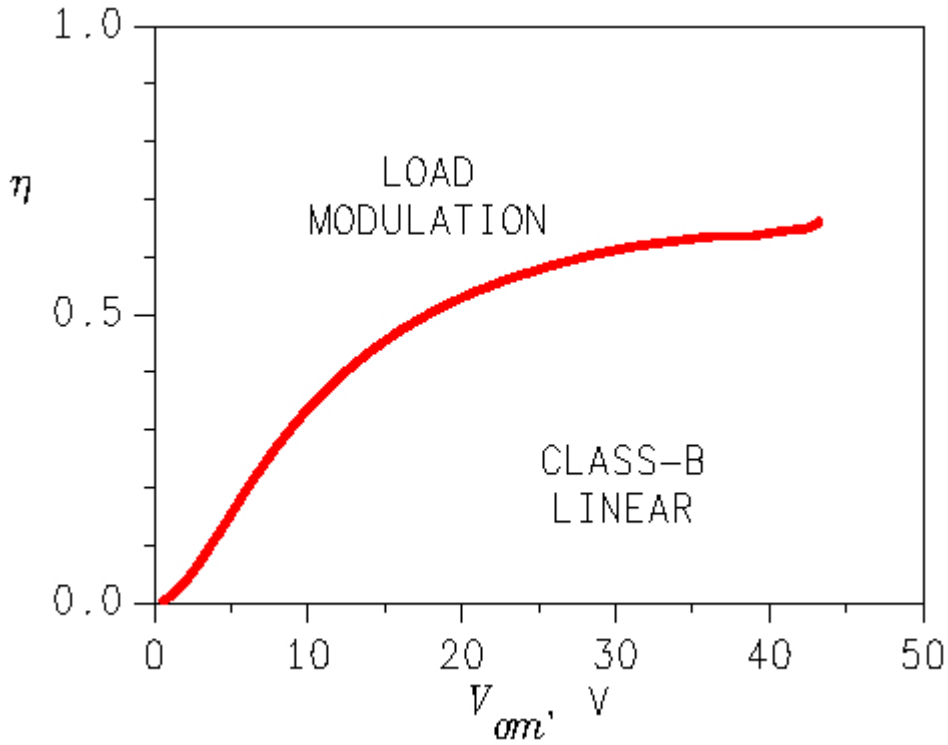




- Vary bias(es) of electronically tuned filter
- Variable load impedance to power amplifier
- Variable output power and amplitude
- Phase information in drive signal
- Wide bandwidth – limited only by bias feed/modulator

U.S. patent 7,202,734

PROTOTYPE LOAD-MODULATED PA



30 MHz

19 W PEP

Varactor = HV MOSFETs

41-dB dynamic range

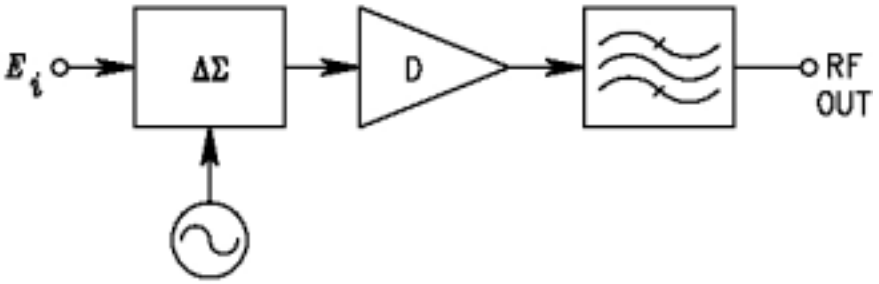
1 variable element

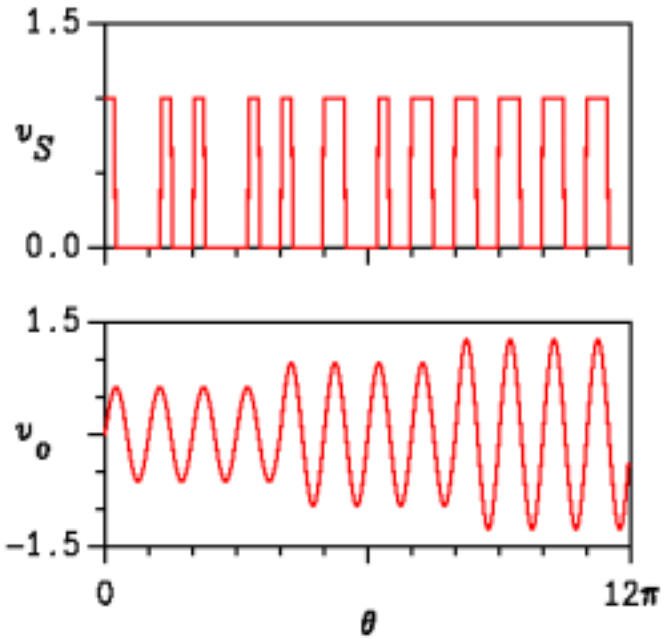
10-dB peak/average ratio

Average efficiency x2.1

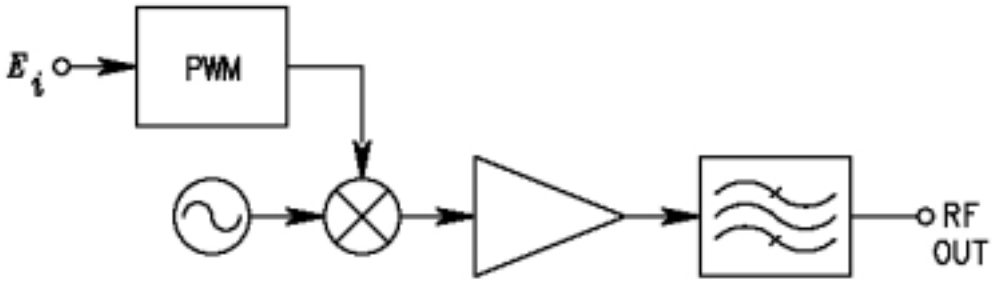
RF PULSE-WIDTH MODULATION

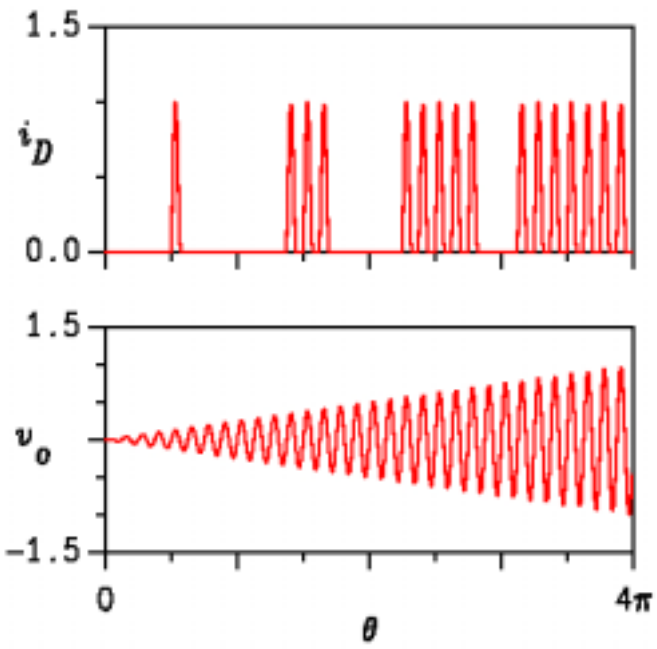
DELTA-SIGMA RF PWM





CARRIER PWM





ARCHITECTURES - TWO CATEGORIES

1. HIGH EFFICIENCY OVER MODULATION ENVELOPE

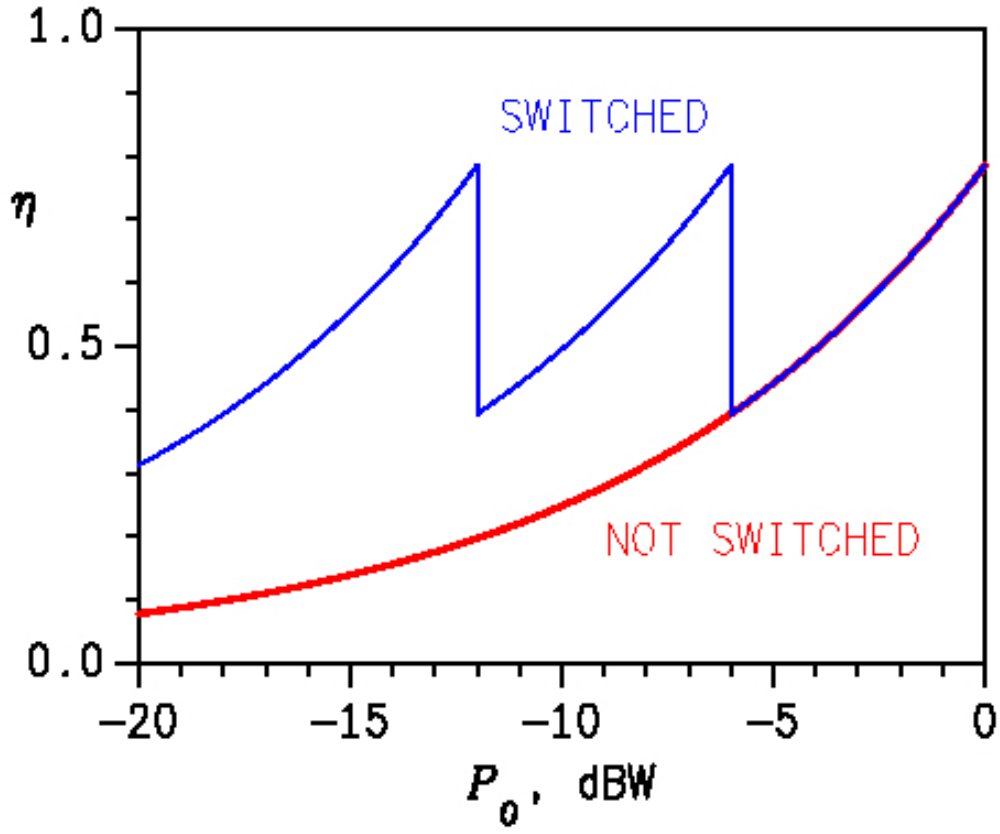
2. HIGH EFFICIENCY OVER DYNAMIC RANGE

EFFICIENCY OVER DYNAMIC RANGE

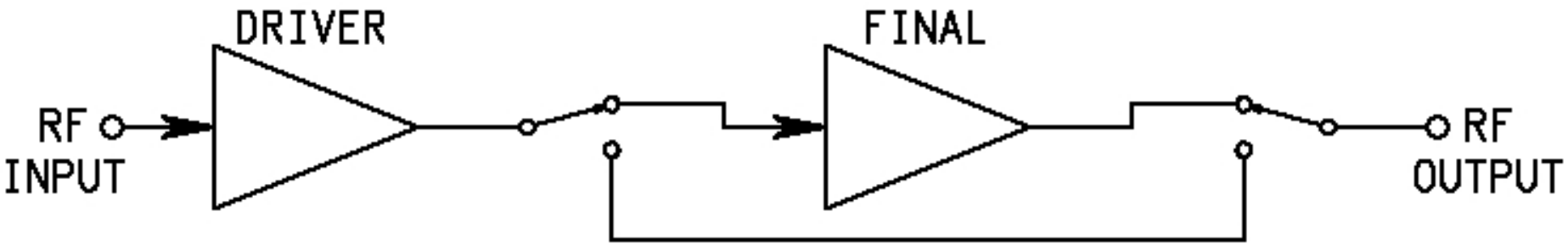
CHARACTERISTICS

- Mobile transmitters
- Wide range of power
- Mostly switched
- Follows PEP, not envelope

PEP EFFICIENCY (TYPICAL)

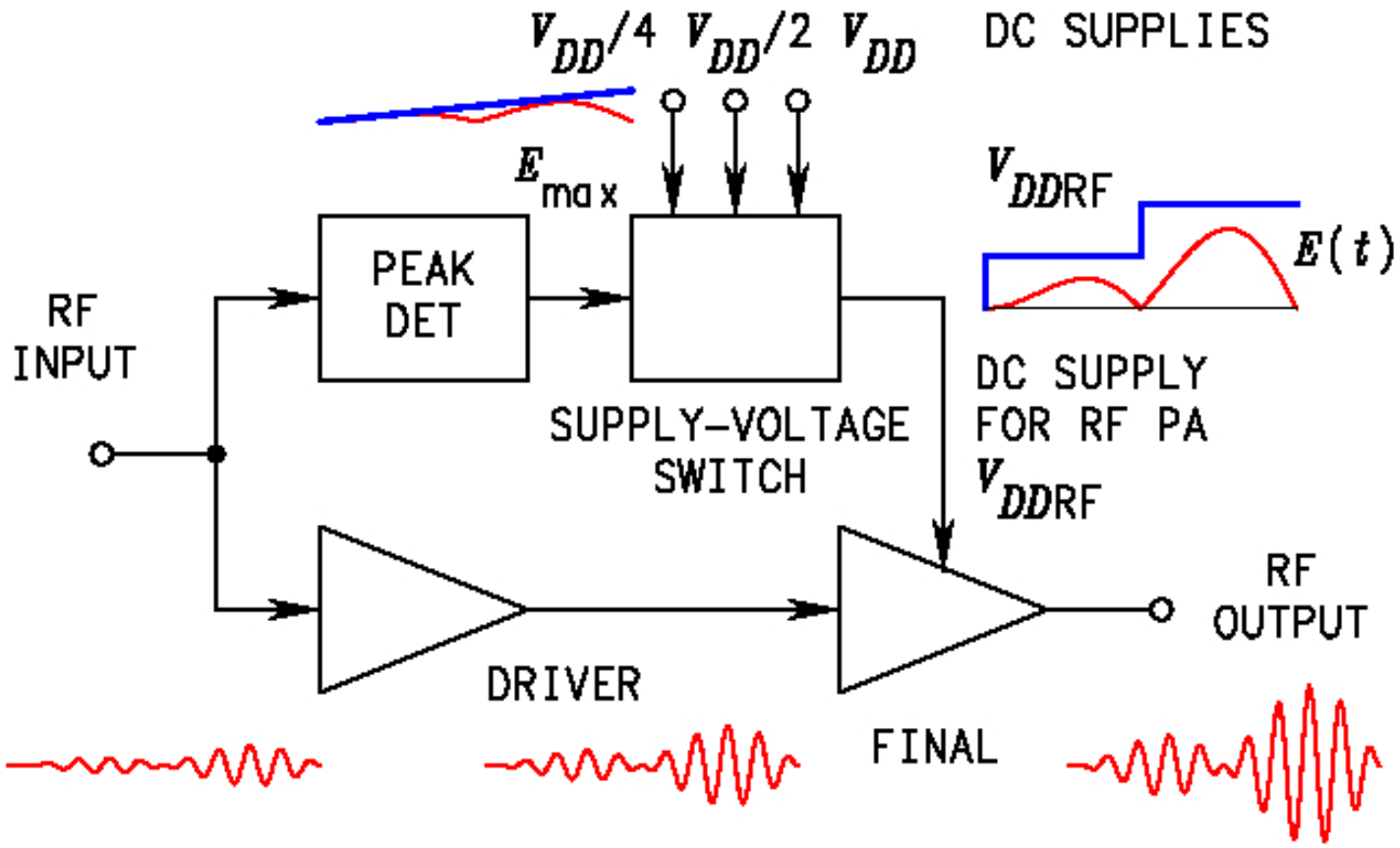


STAGE BYPASSING



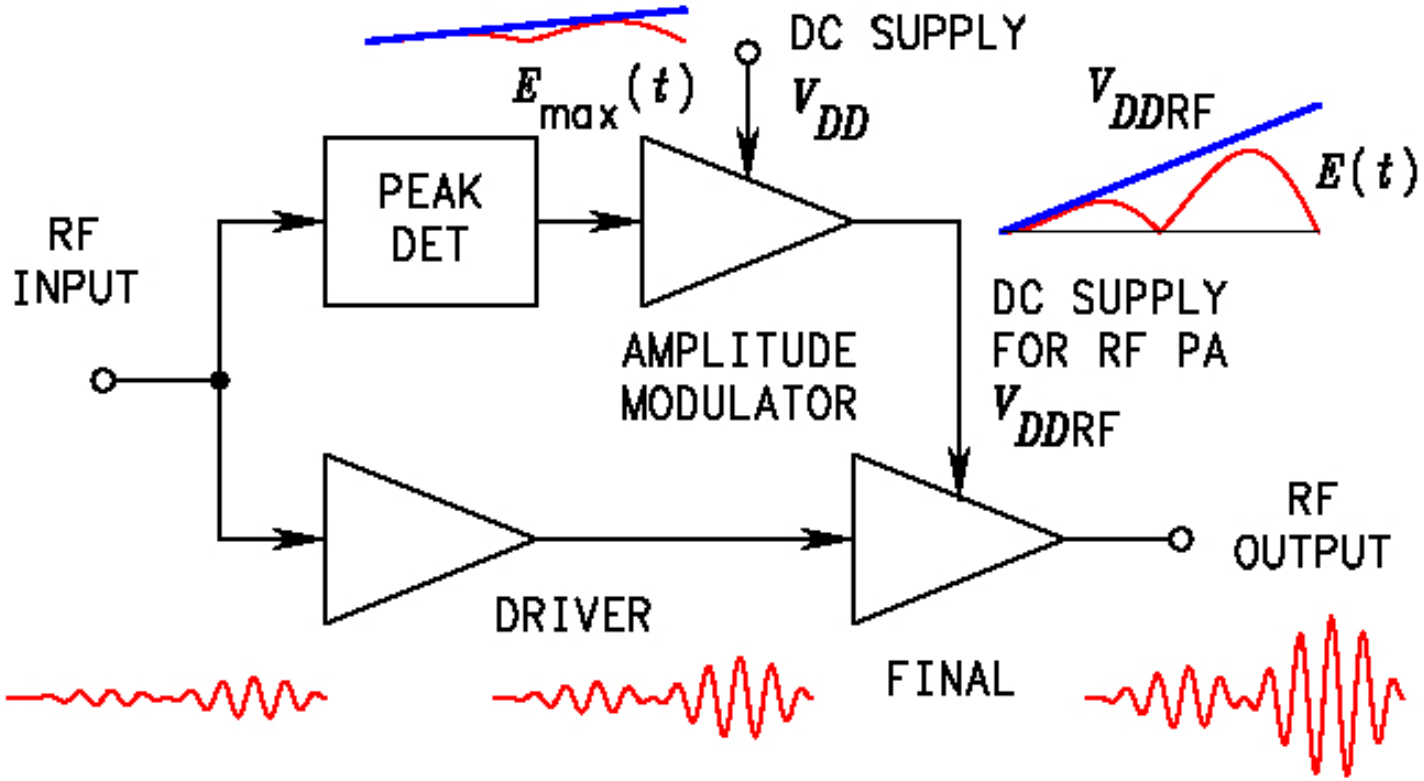
- LOW OUTPUT: Use driver
- HIGH OUTPUT: Use final

ENVELOPE TRACKING - DISCRETE



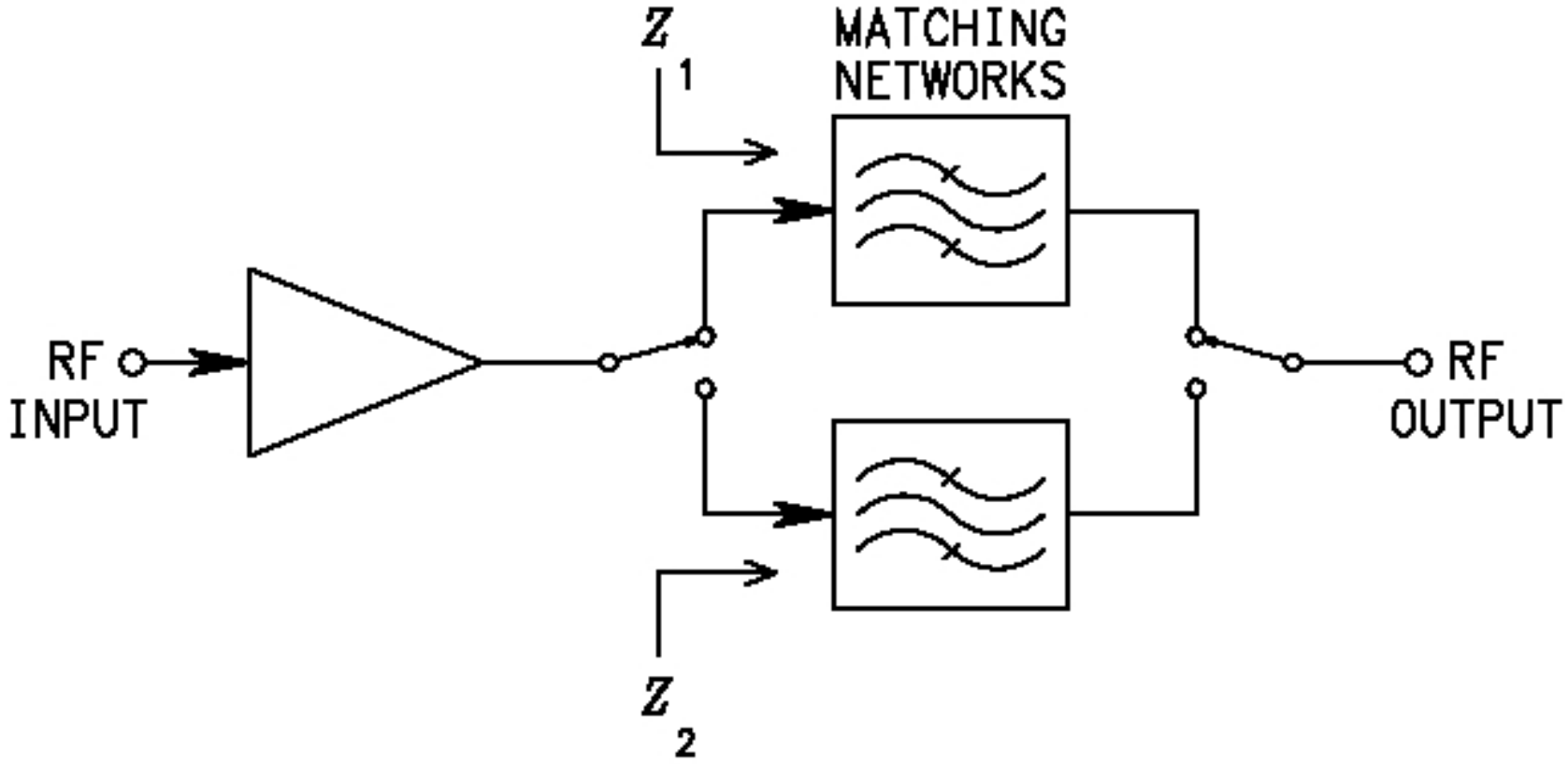
- RF PA: Linear
- Select minimum supply voltage for linear operation
- May cause detuning (mismatch)

ENVELOPE TRACKING - CONTINUOUS



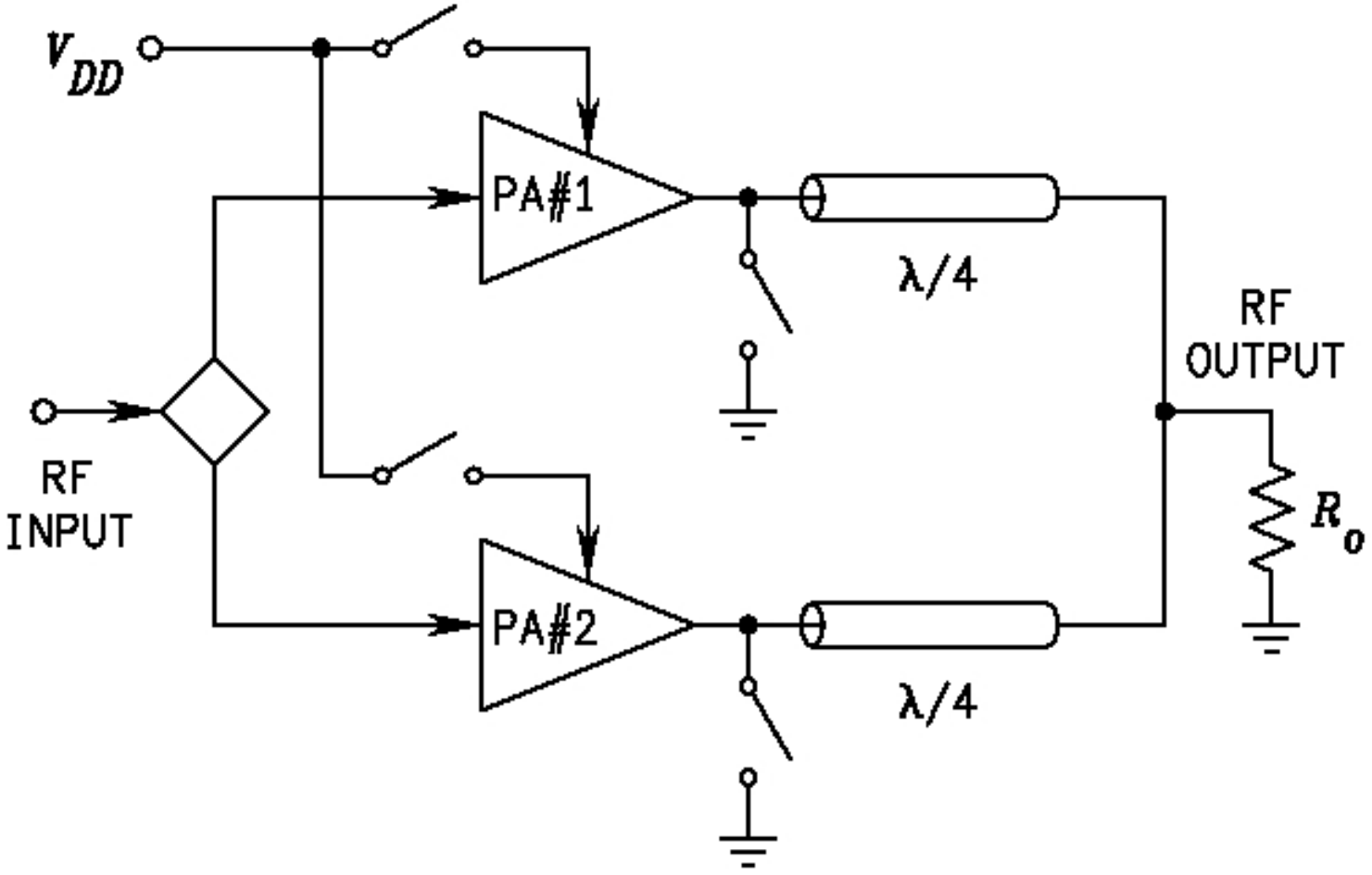
- RF PA: Linear
- Supply voltage = minimum + headroom
- May cause detuning (mismatch)
- Often minimum voltage (boost converter)

LOAD-IMPEDANCE SWITCHING



- High impedance → low power
- Low impedance → high power
- Matched both cases

MULTIPLE SWITCHED PAs



- Number of PAs active ~ P_{oPEP}
- Short PA output → Decouple from output

CONCLUSIONS

Variety of techniques available.

Significant improvements in average efficiency.

Each has advantages and disadvantages.

Combinations possible.

Interesting research to be done.

What is old is sometimes new again.