CLASS C
Class-C Amplifier

- Like class-B, $I_{\text{quiescent}} = 0$
- Unlike class-B, conduction angle $< 180$ deg
- Gain is low since device is turned on for only a short period

Harmonics are shorted

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Class-C Amplifier

- $I_{\text{quiescent}} = 0$
- $I_{dc} < I_{rf} / \pi$
- $P_{out} (rf) < 1/4 \ V_{rf} I_{rf}$
- $P_{in} (dc) = V_o I_{dc}$
- $\eta_{max} = \pi / 4 * (V_{max} - V_{min}) / (V_{max} + V_{min})$

Harmonics are shorted

- $I_{\text{out}}$
- $I_{\text{max}}$
- $V_{\text{min}}$
- $V_{o}$
- $V_{\text{max}}$
- $V_{\text{out}}$
- $V_{\text{ce}}$
- $V_{o}$
- $I_{c}$
- $I_{dc}$
- $V_{rf}$
- time
Load Impedance Is A Resonant Network

Short at all harmonics here

\[ Z = RL \text{ at } fo \]
\[ Z = 0 \text{ at } 2fo, 3fo, 4fo, \ldots \]

Representative Z values

At fo
\[ -j2\Omega \]
\[ j2\Omega \]
\[ 10 \Omega \]

At 2fo
\[ -j1\Omega \]
\[ j4\Omega \]
\[ 10 \Omega \]
Class-C Waveform

\[ I(t) = \begin{cases} 
  i_{PK} \cos I_{DC} & \text{when } i_{PK} \cos > I_{DC} \\
  0 & \text{otherwise}
\end{cases} \]

\[ \cos = \frac{I_{DC}}{i_{PK}} \quad I_{DC} \text{ is the (negative) offset} \]
\[ i_{PK} \text{ is the amplitude} \]

\[ I_{DC} = \frac{1}{2} \int_0^x I( \ ) \cos \quad d = \frac{2}{0} \int_0^x I( \ ) \cos \quad d \]

\[ I_{FUND} = \frac{2}{0} \left( i_{PK} \cos^2 \quad I_{DC} \cos \right) d \]

\[ I_{FUND} = \frac{2}{0} \left( \frac{1}{2} i_{PK} + \frac{1}{4} i_{PK} \sin 2 \quad I_{DC} \sin \right) \]

\[ I_{DC} = \frac{1}{2} (i_{PK} \sin \quad I_{DD} ) \]

\[ I_{FUND} = \frac{i_{PK}}{0} \left( \frac{1}{2} \sin 2 \quad \right) \]
Class-C Conduction

• Φ is the conduction angle during which the current conducts through the transistor. What happens for Φ of pi or 2PI?

\[ I_{\text{FUND}} = \frac{i_{PK}}{\frac{1}{2} \sin 2} \]
Class-C Efficiency

\[ I_{DC} = \frac{i_{PK}}{\sin \theta \cos \theta} \]

\[ = \frac{P_{RF, MAX}}{P_{DC}} = \frac{v_{PK}i_{PK}}{2V_{DD}I_{DC}} = \frac{\frac{1}{2} \sin(2\theta)}{2(\sin(\theta) \cos(\theta))} \]

- As conduction angle approaches 0, the efficiency approaches 100%.
- What is the penalty?
Class C Waveform Analysis

• Calculate efficiency

\[
\frac{1}{2} v_{PK} i_{PK} \frac{i_{pk}}{V_{DC} I_{DC}} = \frac{1}{2} \frac{v_{pk}}{V_{DC}} \frac{i_{pk}}{2} \left( \frac{1}{2} \sin 2 \right) V_{DC} \frac{V_{RF,MAX}}{V_{DC}} f(0)
\]

\[
f(0) = \frac{1}{2} \left( \frac{1}{2} \sin 2 \right)
\]

\[
\rightarrow = \frac{V_{FUND}}{V_{FUND,MAX}} \frac{V_{FUND,MAX}}{V_{DC}} f(0)
\]

\[
= \sqrt{\frac{P_{OUT}}{P_{OUT,MAX}}} \frac{V_{MAX}}{V_{MAX} + V_{MIN}} f(0)
\]

\[
\lim_{0 \to 0} f(0) = 1 \quad \lim_{0 \to \frac{1}{2}} f(0) = \frac{1}{4}
\]
Power Amplifier Comparison

![Diagram showing comparison of output power normalized to Class-A in relation to conduction angle for Class C, B, AB, and A.](image-url)
Class-C Amplifier Efficiency

- Class C has very good efficiency because whenever the device has current, $V_{ds}$ is particularly low.
Class-C Waveform Analysis

• How about the loadline resistance?

\[ R_L = \frac{V_{FUND}}{I_{FUND}} \]

\[ V_{FUND} = \frac{V_{MAX} - V_{MIN}}{2} \]

\[ I_{FUND} = I_S \left( \frac{1}{2} \sin 2 \theta \right) \]

\[ I_{MAX} = I_S \quad I_O = I_S (1 - \cos \theta) \]

\[ I_{FUND} = I_S \left( \frac{1}{2} \sin 2 \theta \right) \]

\[ I_{FUND} = I_S \left( \frac{1}{2} \sin 2 \theta \right) \]

\[ R_L = \frac{V_{MAX} - V_{MIN}}{I_{MAX} \left( \frac{1}{2} \sin 2 \theta \right)}  \]

θ (degrees)
Gain and Conduction Angle

Gain (dB)

Class A
Class B ideal
Class B real
Class AB "ideal"
Class AB "real"
Class C "real"

Pin (dBm)

6dB
Power Amplifier Comparison

• Maximum voltage swing is $2V_o - V_{\text{min}}$
• Gain is 6 dB lower for class-B than class-A, expect it to be even lower than class-C.
• Power density is the same for class A and B but lower for class C.
Other Classes of Amplifiers

• PA research is focused around getting high-power power at high-efficiency.

• Class D Amplifiers
  – Push-pull style amplifier

• Class E/F Amplifiers
  – Switching amplifiers which can allow 100% PAE but require care with harmonics

• Class J Amplifier
  – Overdriven class-A
CLASS F
Class F Amplifier

- Add “harmonic tuning” to Class B amplifier
- Nominally open circuit at odd harmonics
- Short circuit at even harmonics
- (In reality, need to optimize for given transistor)
- $V_{ds}$ begins to look like a square wave
Class F Amplifier

- With added 3rd harmonic \( V_{3fo} = \frac{1}{9} V_{fo} \),
- \( V_{fo} \) can reach the highest value without causing clipping
- \( I_{quiescent} = 0 \)
- \( I_{dc} = I_{ave} = \frac{I_{rf}}{\pi} \)
- \( P_{dc} = V_{DD} I_{ave} \)

\[
= \frac{9}{8} \frac{V_{max}}{4} \frac{V_{min}}{V_{max} + V_{min}}
\]

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Class F Strategy

- Adding 3rd harmonic to voltage flattens its top and bottom, so it begins to approach a square wave.
- With 3rd harmonic added, the fundamental can be increased at fixed signal swing (before clipping).
- Get even better results adding 5th harmonic.
Fourier Series Example

- \( V_{fo} / (Vo/2) = 0.63/0.5 = 1.26 \): This is for perfect square wave (includes all odd harmonics)
- \( V_{fo} / (Vo/2) \approx 9/8 = 1.125 \): This is just 3\(^{rd}\) harmonic
Class F Waveform Analysis

- Is there power delivered to load at $2f_o$? No, $V_{2f_o}=0$
- Is there power delivered to load at $3f_o$? No, $I_{3f_o}=0$
- $P_{rf}=1/2$ $V_{fo}$ $I_{fo}= 1/4$ $V_{fo}$ $I_{rf} = 1/4$ $I_{rf}*(V_{max}-V_{min})/2 * 9/8$
- $P_{dc}= V_{dc}$ $I_{dc} = I_{rf}/\pi*(V_{max}+V_{min})/2$
- Efficiency $=\pi/4 *9/8*(V_{max}-V_{min})/(V_{max}+V_{min})$

$I_{dc}=I_{rf}/\pi$ just as for Class B
$I_{fo} = I_{rf}/2$ just as for Class B
$V_{fo}= RL(fo)$ $I_{fo}$

For Class F
$V_{max}=V_{dc}+8/9$ $V_{fo}$
$V_{min}=V_{dc}- 8/9$ $V_{fo}$
$\Rightarrow V_{fo}=(V_{max}-V_{min})/2*9/8$
$V_{max}= V_{dc}+V_{fo}$
$V_{min}=V_{dc}-V_{fo}$ for class B
Class F Amplifier Implementation: Accounting for Output Capacitance

freq (100.0 MHz to 10.00 GHz)

S(1,1)
1.096E9
0.826 / 141.441
m1
2.089E9
0.793 / 99.795
m2
2.951E9
0.998 / -2.634
m3

freq=
S(1,1)=0.252 / -79.574
impedance = Z0 * (0.963 - j0.509)
1.096GHz

m2
freq=2.089GHz
S(1,1)=1.000 / -179.915
impedance = Z0 * (1.514E-7 - j7.444E-4)
2.089GHz

m3
freq=2.951GHz
S(1,1)=0.998 / -2.634
impedance = Z0 * (1.517 - j43.448)
2.951GHz
Class F Amplifier

• Alternative Implementation

Short at all harmonics here

$Z_0 = RL$

$\lambda_0/4$

$Z = RL$ at $f_0$

$Z = 0$ at $2f_0$, $4f_0$

$Z = \infty$ at $3f_0$, $5f_0$,...

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Class F Example

- David Schmelzer and Stephen I. Long, CSICS 2006
- GaN FETs at 2GHz
- Class F amplifier

![Class F Example Diagram](image)

86% PAE, 17W
Harmonic Load Tuning

\[ X_2 = \text{Im}(Z_{\text{net}}) \text{ at } 2f_0 \]
\[ X_3 = \text{Im}(Z_{\text{net}}) \text{ at } 3f_0 \]
Other Approaches for High-Efficiency

• Control the voltage and current waveforms to prevent conduction while the voltage
• Class D: Switch current and voltage
• Class E: ZVS and ZVS derivative switching
• Class F⁻¹