Alimentations RF: Principes et utilisations

RF Power Sources: Principles and Use

Erik V. Johnson

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Alim-Plasma
QUELLE ALIMENTATION POUR QUEL PLASMA?
Orléans, 1-3 avril 2019

GN 500

GN Range: 100 kHz - 200 MHz / 500 W CW

PRÂNA
Broadband power amplifiers

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Prana GN 500

- Class A solid state
- Broadband (instantaneous single band): 100 kHz – 200 MHz
- Frequency extension between 80 kHz to 250 MHz upon request (with limited specifications)
- Typical output power : 500 W CW
- Linear output power (1 dB compression) guaranted with harmonics <-20 dBc:
  - P1dB > 450 W and H < -20 dBc up to 100 MHz and
  - P1dB > 180 W and H < -20 dBc from 100 MHz to 200
- Air cooling: self contained fans
- Can operate in full mismatch conditions without damage
- Reliable, efficient and robust
- 19" Rack
- 3 years standard warranty

Maintenance

- Amplifier designed for minimal maintenance
  - Easy access to all parts
  - Modular design
  - Repairs with minimum adjustments
- Rapid diagnostic
- Minimal downtime
- Contract for preventive and corrective maintenance available

Applications

- EMC tests
- RF tests and instrumentation
- Radiocommunication
- Measurement and research laboratories

Versions

- GN 500 D amplifier with:
  - Multicolor LCD display with touch panel
  - Digital control
  - IEEE 488 GPIB, Ethernet, USB, RS232 Communications
  - Temperature controlled fans
  - Safety interlock
- GN 500 DC : GN 500 D with :
  - Integrated dual directional coupler
  - Display of instantaneous incident and reflected power

GN Range

- GN 500 => 500 W CW
- GN 1000 => 1000 W CW
- GN 2000 => 2000 W CW
- GN 3500 => 3500 W CW
- GN 7000 => 7000 W CW
- GN 12000 => 12000 W CW
- GN 40 => 40 W CW

Extra

- External coupler
- Supply and integration inside a cabinet
- Bulk Current Injection + Calibration JIG
- RF Power cable
- Switching unit

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GN 500

GN Range: 100 kHz - 200 MHz / 500 W CW

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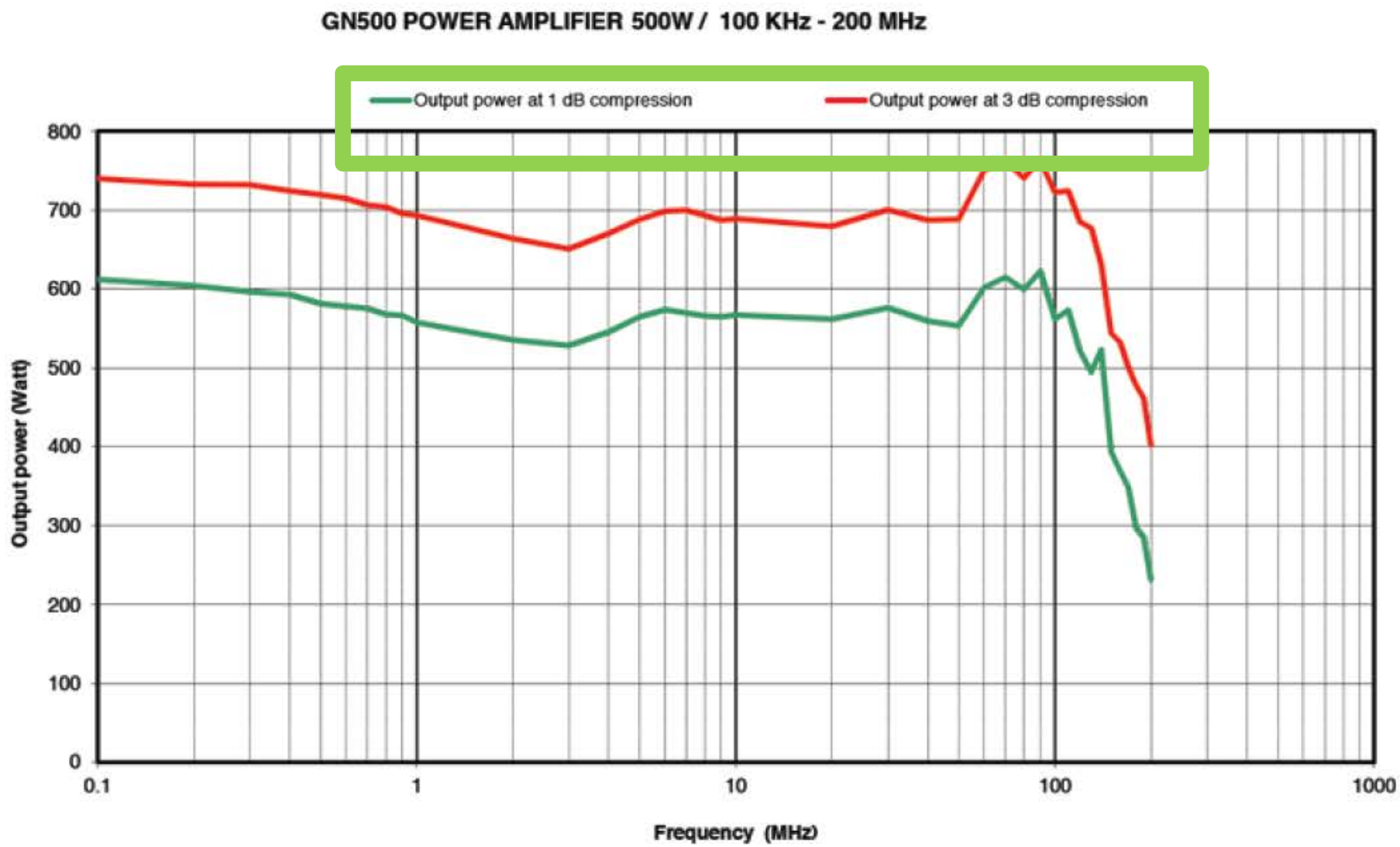

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Specifications

Frequency bandwidth	100 kHz - 200 MHz (Frequency extension between 80 kHz to 250 MHz upon request)
Typical output power	500 W
Power at 3 dB compression	550 W min. up to 100 MHz / 280 W min. from 100 MHz to 200 MHz
Power at 1 dB compression	450 W min. up to 100 MHz / 180 W min. from 100 MHz to 200 MHz
Harmonics distortion	H2,H3 < -20 dBc for the output power at 1 dB compression limit
Class type	Class A
Gain	55 dB
Linear power gain flatness	± 3 dB max
Mismatch tolerance	infinite without damage
Input impedance	50 ohms / VSWR: 2:1max
Output impedance	50 ohms / VSWR: 2:1max
Input power	+10 dBm max.
RF input connector	[illegible]
RF output connector	Type N fem. (front or rear panel) – other connector type on request
Safety interlock	Connector type BNC
Digital control	Transistors, power supplies, temperatures and fans
Communication interfaces	Ethernet, USB, GPIB, RS232
Color LCD Display with touch screen	Status, faults, (direct and reverse instantaneous power for DC version)
Ambient operating temperature	0 °C / + 35 °C
Room temperature storage	-20 °C / +70 °C
Cooling	Forced air with fan speed control (for D version): 120 l/sec max. (self contained fans)
Power voltage	[illegible] Hz, single phase
Rated current	7.4 A at 230 VAC
Dimensions	640 x 840 x 312 mm (7U) / 25.2 x 33.1 x 12.3 in (7U)
Weight	44 kg / 97 lb

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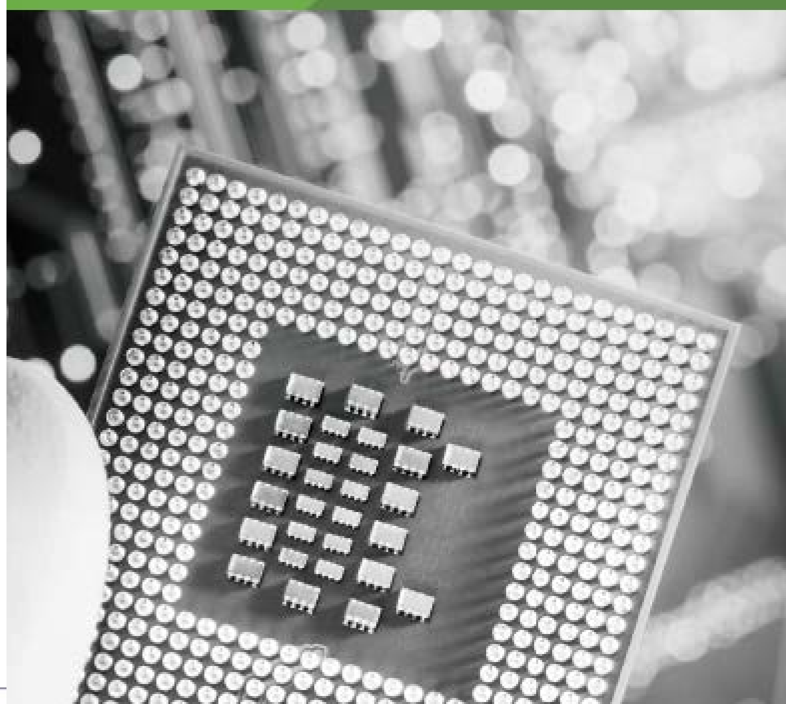
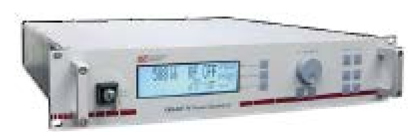
Advanced Energy

CESAR RF POWER SUPPLIES

ROBUST RF POWER SUPPLIES FOR DEPENDABLE PERFORMANCE
IN DEMANDING PLASMA APPLICATIONS





Output Frequency

2, 4, 13.56, 27.12, 40.68 MHZ

Power Output

300 W to 5 kW

Input Voltage

200 and 400 VAC

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Cesar RF Power Supplies

The robust and versatile Cesar® platform offers exceptionally consistent RF power-delivery performance, as well as a diverse selection of models, each with a unique set of features and capabilities (2, 4, 13.56, 27.12, and 40.68 MHz; 0.3 to 5 kW; with a variety of user interfaces and input options). This enables you to choose a unit suited specifically to your application — without lengthy custom-generator lead times.

High-quality components and a low part count maximize reliability and product lifetime, making the most of your investment — and your process productivity. A comprehensive, yet highly intuitive operating menu, accessible on the unit's active front panel and displayed on a large LCD, provides unparalleled ease — increasing operator efficiency and minimizing training costs.

The economical Cesar RF power supply platform includes a wide variety of models, each with a comprehensive and unique feature set, to suit most any demanding plasma-based application.

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Product Highlights

- Increased process uptime
- Enhanced operational ease and flexibility
- Customized performance without custom-unit lead times
- Long-term ease of use and cost savings
- World-class service and support
- Compact, streamlined design
- Standard platform packaging
- High efficiency — less heat generated
- Two analog user port options
- SEMI™ compliance (meets or exceeds standards)

Typical Application

Cesar RF power supplies offer customized performance for most any plasma-based application, including:

- HDP-CVD
- PECVD
- Etch — ICP/RIE
- PVD
- Plasma cleaning

Multiple Options
(Feature Set Varies According to Model)

- Power Output (Models from 0.3 to 5 kW)
- Analog I/O Type (25 and 15 Pin)
- Output Frequency (2, 4, 13.56, 27.12, and 40.68 MHz models)
- Serial I/O Type (RS-232, Ethernet, or Profibus
- Input Voltage (200 and 400 VAC)

Standard Features
(All Models)

- CEX (Phase Synchronization) Mode
- Compact, Rack-Mountable Package
- Multiple Protection Features
- Active Front Panel
- Advanced Operating Men

Increased Process Uptime, High Product Reliability

The Cesar RF power supply's robust, streamlined design is built from the highest-quality parts available and uses fewer components than competing products. This minimizes the chance of malfunction, wear, or breakage, even under the harsh conditions of plasma processing. Its highly efficient class E switchmode design also generates less heat, reducing temperature stress on critical components.

Dependable Performance

Designed to maintain a tight performance under even the most demanding conditions, the Cesar RF power supply handles high load mismatches, remaining fully functional at rated reflected power (pre-set between 20 and 40%, depending on model).

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Outline – RF Power Sources

- Frequencies of operation
  - ITU/STM Frequency bands for RF plasmas
  - Amplifiers vs Power Sources
- Input and Output Power
  - Expected impedance and matching
  - Gain compression
  - Harmonics (THD and dBc)
- Classes of Amplifier
  - Class A – Wideband amplifier
  - Classes B to E – Narrow band

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What do we mean by RF plasma excitation

Technically, all frequencies at which we can **generate EM** waves through oscillations in a macroscopic dipole/antenna are **radio frequencies**.

Direct current (0 Hz) does not generate an EM wave, and optical frequency waves are not generated in the same way (and physics is different).

For plasmas, we are particularly interested in the band of frequencies where electrons can respond but ions are too heavy, and things are still technologically manageable.

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Radio Frequencies and ISM Bands

International Telecommunications Union has split up spectrum into named bands.

Frequency range	Wavelength range	ITU designation		IEEE bands[5]
		Full name	Abbreviation[6]	
3–30 Hz	10^5–10^4 km	Extremely low frequency	ELF	N/A
30–300 Hz	10^4–10^3 km	Super low frequency	SLF	N/A
300–3000 Hz	10^3–100 km	Ultra low frequency	ULF	N/A
3–30 kHz	100–10 km	Very low frequency	VLF	N/A
30–300 kHz	10–1 km	Low frequency	LF	N/A
300 kHz – 3 MHz	1 km – 100 m	Medium frequency	MF	N/A
3–30 MHz	100–10 m	High frequency	HF	HF
30–300 MHz	10–1 m	Very high frequency	VHF	VHF
300 MHz – 3 GHz	1 m – 10 cm	Ultra high frequency	UHF	UHF, L, S
3–30 GHz	10–1 cm	Super high frequency	SHF	S, C, X, Ku, K, Ka
30–300 GHz	1 cm – 1 mm	Extremely high frequency	EHF	Ka, V, W, mm
300 GHz – 3 THz	1 mm – 0.1 mm	Tremendously high frequency	THF	N/A

Frequencies of 1 GHz and above are conventionally called microwave,[7] while frequencies of 30 GHz and above are designated millimeter wave.

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Band name	Abbrev.	ITU band #	Frequency	Example Uses
Extremely low frequency	ELF	1	3–30 Hz	Communication with submarines
Super low frequency	SLF	2	30–300 Hz	Communication with submarines
Ultra low frequency	ULF	3	300–3,000 Hz	Submarine communication, communication within mines
Very low frequency	VLF	4	3–30 kHz	Navigation, time signals, submarine communication, wireless heart rate monitors, geophysics
Low frequency	LF	5	30–300 kHz	Navigation, time signals, AM longwave broadcasting (Europe and parts of Asia), RFID, amateur radio
Medium frequency	MF	6	300–3,000 kHz	AM (medium-wave) broadcasts, amateur radio, avalanche beacons
High frequency	HF	7	3–30 MHz	Shortwave broadcasts, citizens band radio, amateur radio and over-the-horizon aviation communications, RFID, over-the-horizon radar, automatic link establishment(ALE) / near-vertical incidence skywave (NVIS) radio communications, marine and mobile radio telephony
Very high frequency	VHF	8	30–300 MHz	FM, television broadcasts, line-of-sight ground-to-aircraft and aircraft-to-aircraft communications, land mobile and maritime mobile communications, amateur radio, weather radio
Ultra high frequency	UHF	9	300–3,000 MHz	Television broadcasts, microwave oven, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS and two-way radios such as land mobile, FRS and GMRS radios, amateur radio, satellite radio, Remote control Systems, ADSB
Super high frequency	SHF	10	3–30 GHz	Radio astronomy, microwave devices/communications, wireless LAN, DSRC, most modern radars, communications satellites, cable and satellite television broadcasting, DBS, amateur radio, satellite radio
Extremely high frequency	EHF	11	30–300 GHz	Radio astronomy, high-frequency microwave radio relay, microwave remote sensing, amateur radio, directed-energy weapon, millimeter wave scanner, wireless LAN (802.11ad)
Terahertz or Tremendously high frequency	THz or THF	12	300–3,000 GHz	Experimental medical imaging to replace X-rays, ultrafast molecular dynamics, condensed-matter physics, terahertz time-domain spectroscopy, terahertz computing/communications, remote sensing,

Reserved and ISM Bands

- Certain frequency bands are **reserved** for telecommunications, and one needs a license to broadcast in these bands ("spectrum allocation" for TV, radio, etc).

- The **industrial, scientific and medical (ISM) radio bands** are radio bands (portions of the radio spectrum) reserved internationally for the use of radio frequency (RF) energy for industrial, scientific and medical purposes other than telecommunications.[1]
- **Examples of applications** in these bands include radio-frequency process heating, microwave ovens, and medical diathermy machines.
- The powerful emissions of these devices can **create electromagnetic interference and disrupt radio communication** using the same frequency, so these devices were limited to certain bands of frequencies.
- In general, communications equipment operating in these bands must tolerate any interference generated by ISM applications.
- Despite the intent of the original allocations, in recent years the fastest-growing uses of these bands have been for short-range, low power wireless communications systems (Cordless phones, Bluetooth devices, wireless computer networks (WiFi)).

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Center frequency	Bandwidth	Type	Availability	Licensed users
6.78 MHz	30 KHz	A	Subject to local acceptance	FIXED SERVICE & Mobile service
13.56 MHz	14 KHz	B	Worldwide	FIXED & Mobile services except Aeronautical mobile (R) service
27.12 MHz	326 KHz	B	Worldwide	FIXED & MOBILE SERVICE except Aeronautical mobile service, CB Radio
40.68 MHz	40 KHz	B	Worldwide	Fixed, Mobile services & Earth exploration-satellite service
433.92 MHz	1.74 MHz	A	only in Region 1, subject to local acceptance	AMATEUR SERVICE & RADIOLOCATION SERVICE, additional apply the provisions of footnote 5.280. For Australia see footnote AU.
915 MHz	26 MHz	B	Region 2 only (with some exceptions)	FIXED, Mobile except aeronautical mobile & Radiolocation service; in Region 2 additional Amateur service
2.45 GHz	1 GHz	B	Worldwide	FIXED, MOBILE, RADIOLOCATION, Amateur & Amateur-satellite service
5.8 GHz	150 MHz	B	Worldwide	FIXED-SATELLITE, RADIOLOCATION, MOBILE, Amateur & Amateur-satellite service
24.125 GHz	250 MHz	B	Worldwide	AMATEUR, AMATEUR-SATELLITE, RADIOLOCATION & Earth exploration-satellite service (active)
61.25 GHz	500 MHz	A	Subject to local acceptance	FIXED, INTER-SATELLITE, MOBILE & RADIOLOCATION SERVICE
122.5 GHz	1 GHz	A	Subject to local acceptance	EARTH EXPLORATION-SATELLITE (passive), FIXED, INTER-SATELLITE, MOBILE, SPACE RESEARCH (passive) & Amateur service
245 GHz	2 GHz	A	Subject to local acceptance	RADIOLOCATION, RADIO ASTRONOMY, Amateur & Amateur-satellite service

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Amplifier vs Source

Prana GN 500

- Class A solid state
- Broadband (instantaneous single band): 100 kHz – 200 MHz
- Frequency extension between 80 kHz to 250 MHz upon request (with limited specifications)
- Typical output power : 500 W CW
- Linear output power (1 dB compression) guaranted with harmonics <-20 dBc:
  - P1dB > 450 W and H < -20 dBc up to 100 MHz and
  - P1dB > 180 W and H < -20 dBc from 100 MHz to 200
- Air cooling: self contained fans
- Can operate in full mismatch conditions without damage
- Reliable, efficient and robust
- 19" Rack
- 3 years standard warranty

Broadband RF Amplifier operating from LF to VHF

Multiple Options

(Feature Set Varies According to Model)

- Power Output (Models from 0.3 to 5 kW)
- Analog I/O Type (25 and 15 Pin)
- Output Frequency (2, 4, 13.56, 27.12, and 40.68 MHz models)
- Serial I/O Type (RS-232, Ethernet, or Profibus
- Input Voltage (200 and 400 VAC)

RF Power Source operating in ISM bands
Has internal oscillator
Designed for single frequency operation

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I/O Impedance and Power

Typical output power	500 W
Power at 3 dB compression	550 W min. up to 100 MHz / 280 W min. from 100 MHz to 200 MHz
Power at 1 dB compression	450 W min. up to 100 MHz / 180 W min. from 100 MHz to 200 MHz
Harmonics distortion	H2,H3 < -20 dBc for the output power at 1 dB compression limit
Class type	Class A
Gain	55 dB
Linear power gain flatness	± 3 dB max
Mismatch tolerance	infinite without damage
Input impedance	50 ohms / VSWR: 2:1max
Output impedance	50 ohms / VSWR: 2:1max
Input power	+10 dBm max.

- Input and Output characteristic impedance is 50 ohms
- Optimal power coupling is achieved when a 50 ohm load is applied (for any other type of load, impedance matching network is necessary so that output « sees » 50 ohms).
- If any other impedance is seen, **mismatch,** and power will be reflected back into amplifier

Designed to maintain a tight performance under even the most demanding conditions, the Cesar RF power supply handles high load mismatches, remaining fully functional at rated reflected power (pre-set between 20 and 40%, depending on model).

- Power gain is given in dB (divide by 10 and put into exponent, 55dB = $10^{5.5}$)

- dBm is decibels relative to one milliwatt (30 dBm = 10^3 mW = 1W)

- Since impedance is 50 ohms, $P = V_{peak}^2/2(50)$
  - For this amp, max input power 10 dBm = 10 mW = 0.01W
  - Maximum peak input voltage is 1V ($V_{pk\text{-}pk}$ = 2V)

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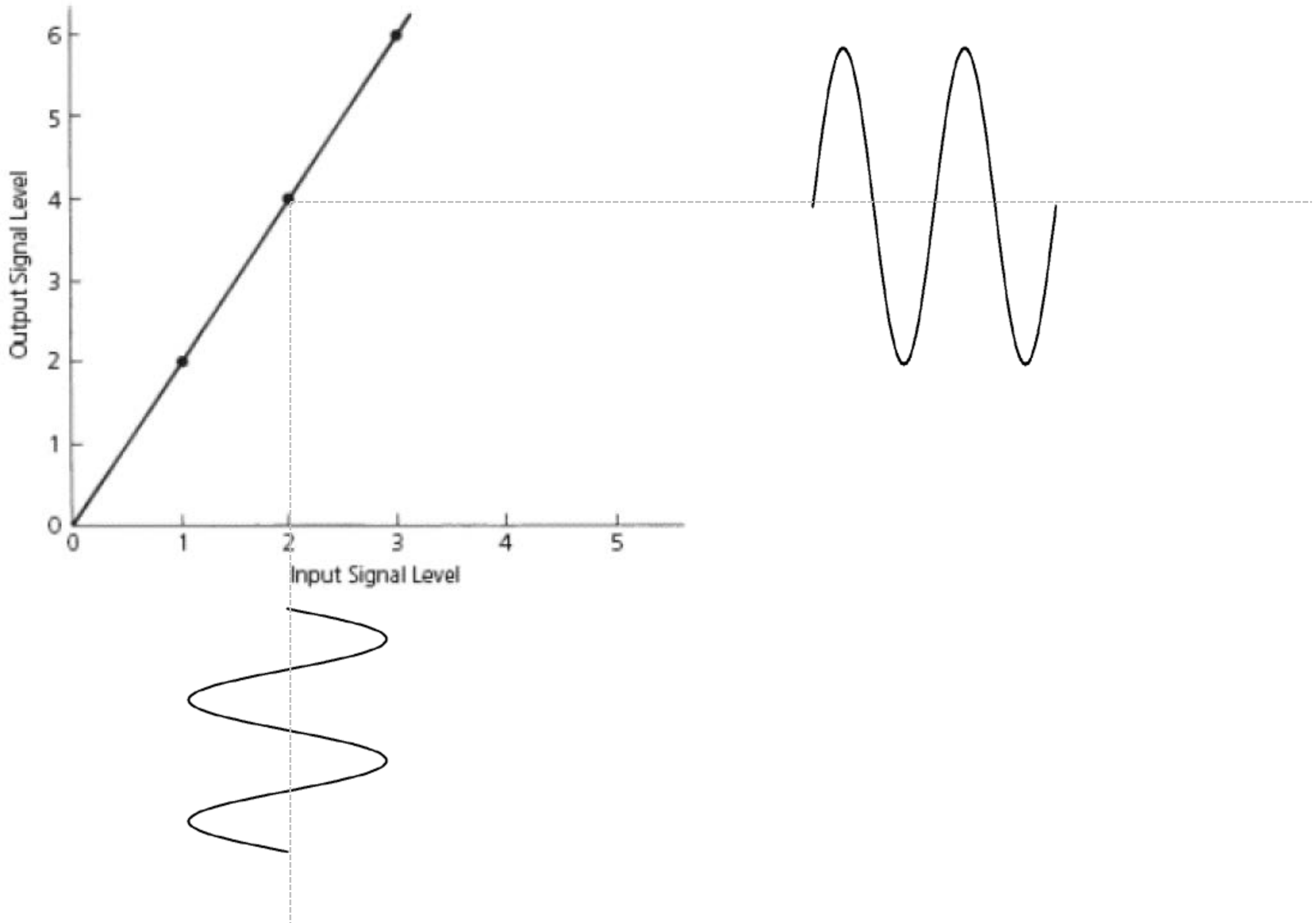
Gain Linearity

If the voltage out is proportional to the voltage in, then the gain is linear.
Obviously, either always or at some level of input voltage, this will no longer be true



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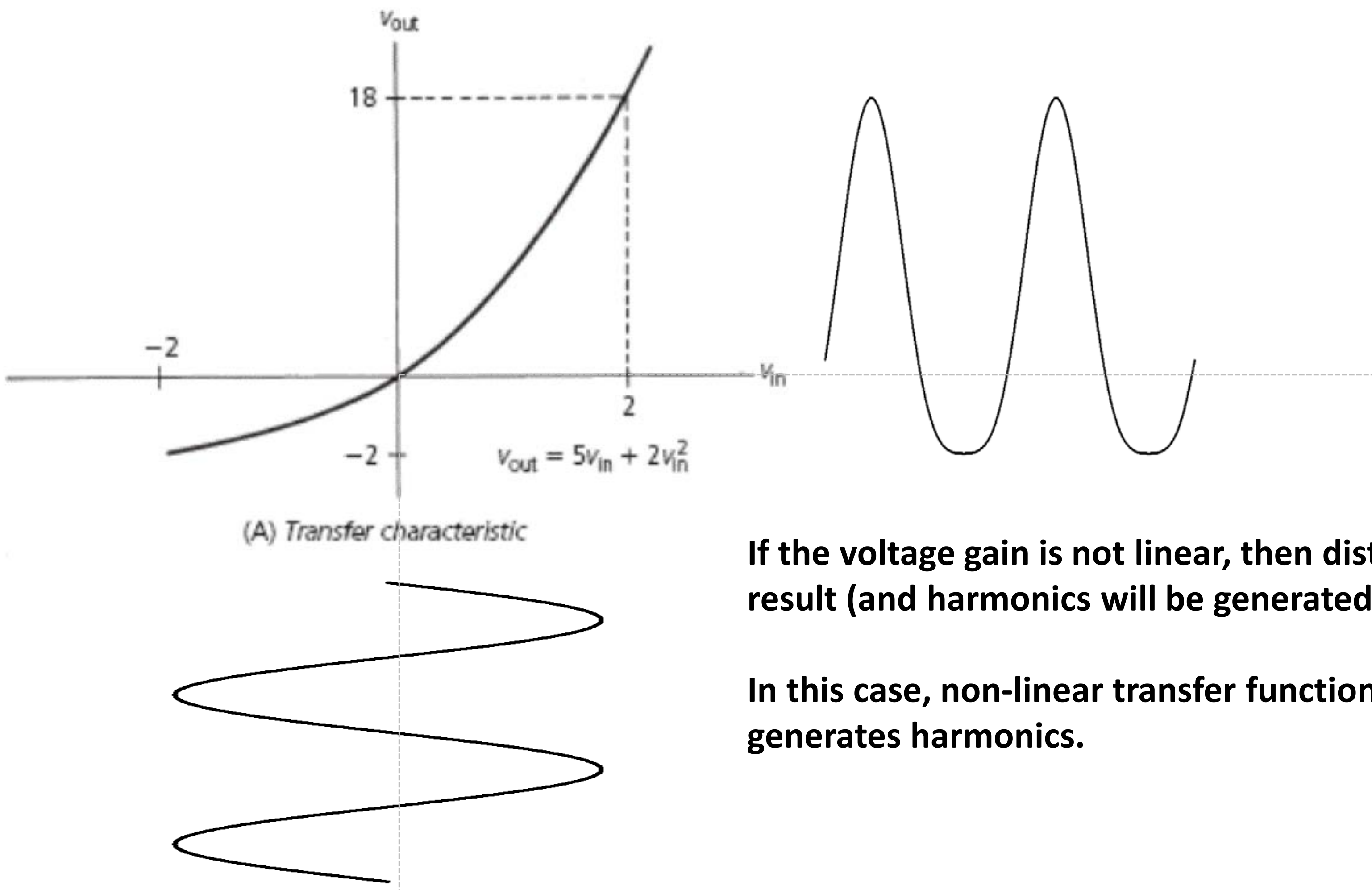
Gain Non-Linearity



(A) Transfer characteristic

If the voltage gain is not linear, then distortion will result (and harmonics will be generated).

In this case, non-linear transfer function around 0 generates harmonics.

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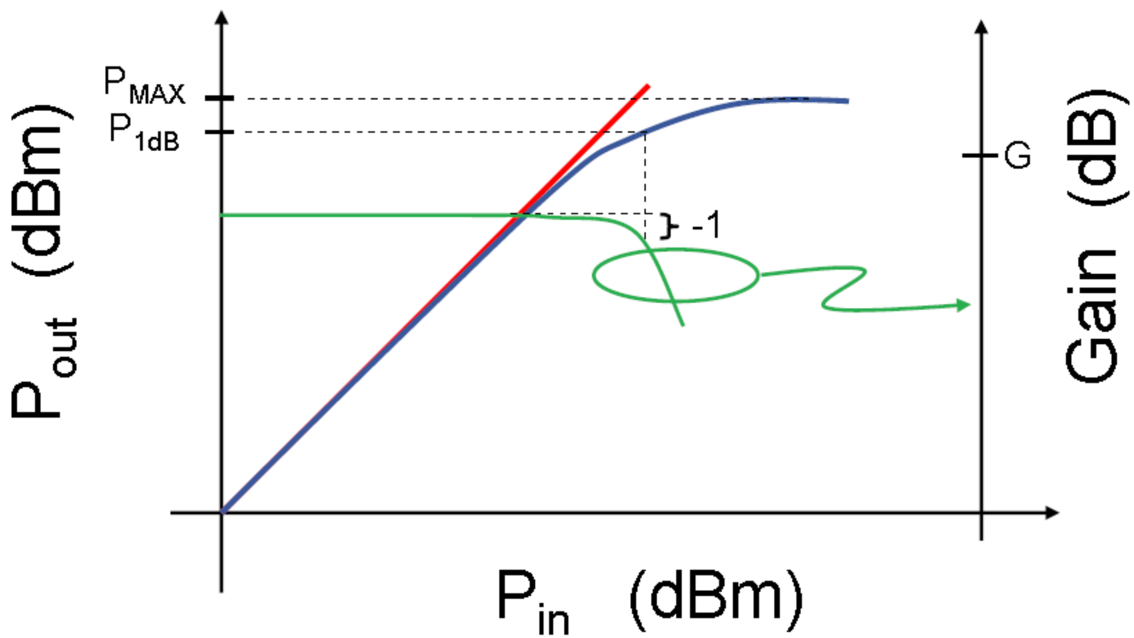
Gain Compression

As maximum output power is approached, gain saturates.
This will depend on the frequency as well
Notice this will also cause harmonics to be created.



Power at 3 dB compression	550 W min. up to 100 MHz / 280 W min. from 100 MHz to 200 MHz
Power at 1 dB compression	450 W min. up to 100 MHz / 180 W min. from 100 MHz to 200 MHz
Harmonics distortion	H2,H3 < -20 dBc for the output power at 1 dB compression limit

dBc is decibels below carrier frequency

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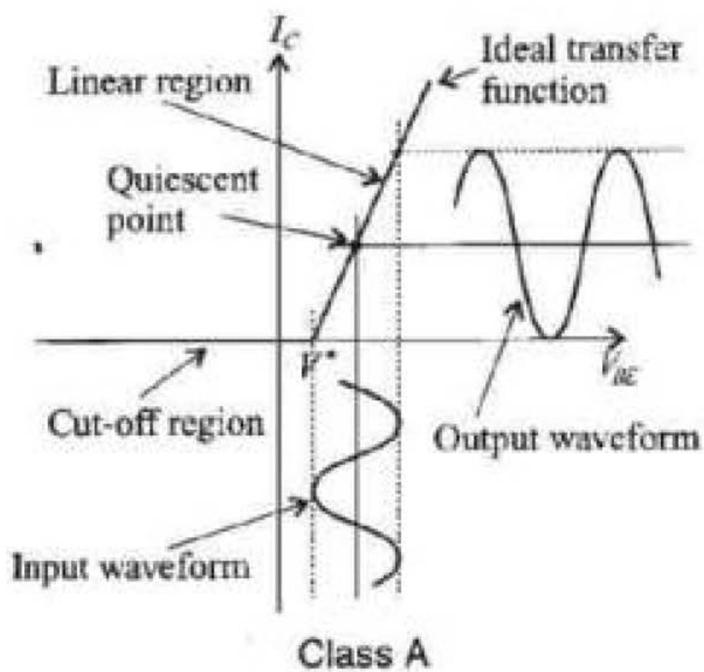
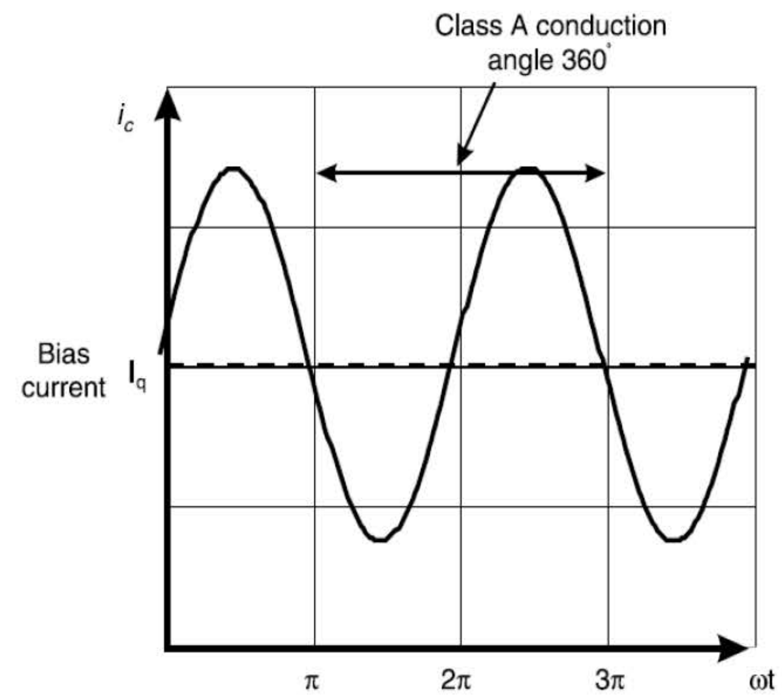
Class A Amplifiers

Class A

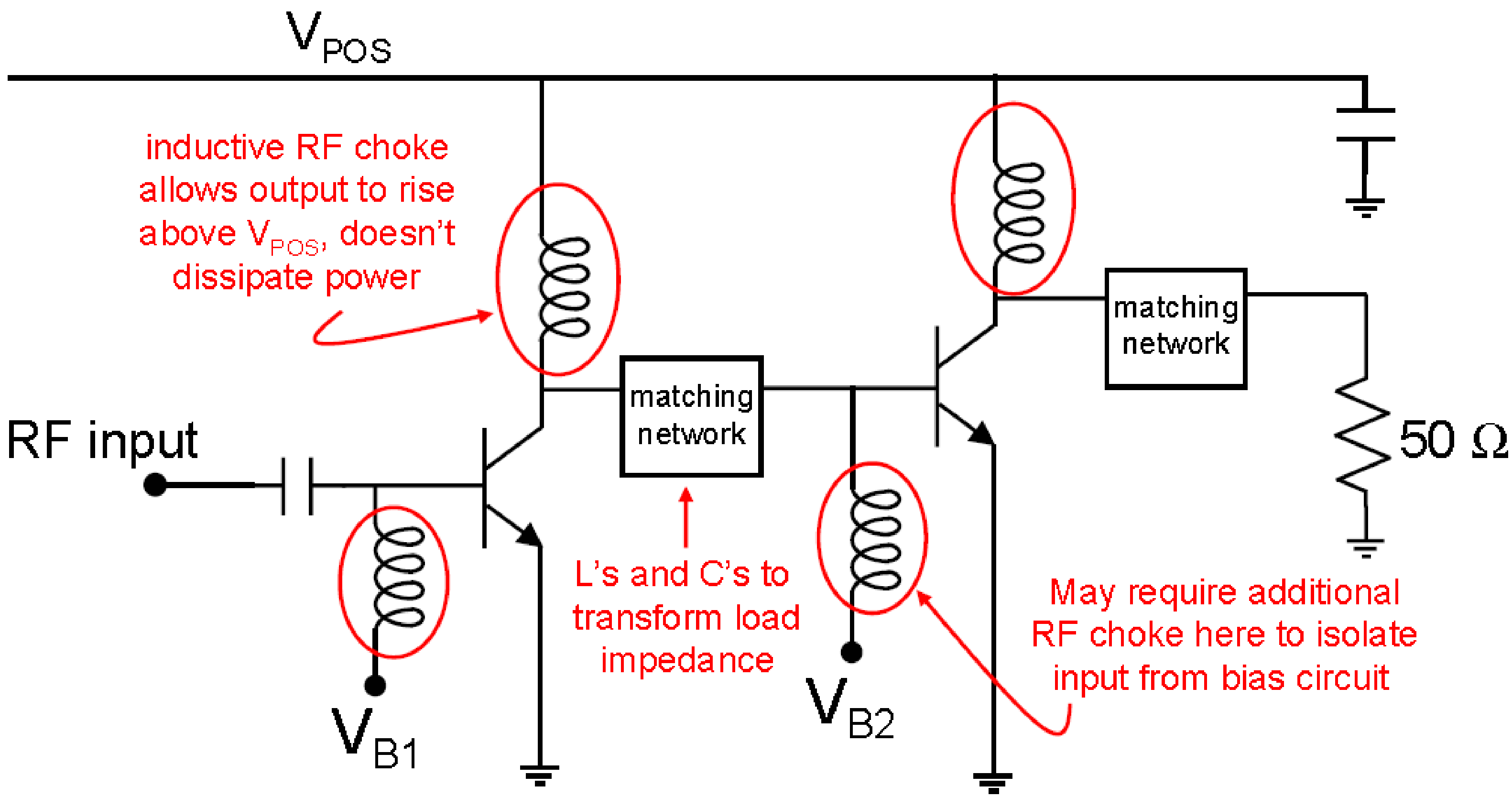




Class A Amplifiers

Class A

Typical 2-stage RF PA design



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Dis/Advantages of Class A

Advantages

- Provides linear amplification over a wide range of output powers and frequencies
- Great when relative magnitudes of signals matter (AM modulation) or multiple frequencies are used
- Can be made totally insensitive to reflected power

Disadvantages

- Power consumed within amplifier (in transistors) will always be V I
- To ensure linearity, quiescent point (operating point with no signal) is at point that consumes ½ maximum power.
- Power is consumed even when no signal is applied
- Total efficiency is 50% (maximum)
- Overkill if signal is quasi-single frequency and constant envelope (30-100 € / Watt RF)

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Dis/Advantages of Class A

Specifications

500 W output power

Frequency bandwidth	100 kHz - 200 MHz (Frequency extension between 80 kHz to 250 MHz upon request)
Typical output power	500 W
Power at 3 dB compression	550 W min. up to 100 MHz / 280 W min. from 100 MHz to 200 MHz
Power at 1 dB compression	450 W min. up to 100 MHz / 180 W min. from 100 MHz to 200 MHz
Harmonics distortion	H2,H3 < -20 dBc for the output power at 1 dB compression limit
Class type	Class A
Gain	55 dB
Linear power gain flatness	± 3 dB max
Mismatch tolerance	infinite without damage
Input impedance	50 ohms / VSWR: 2:1max
Output impedance	50 ohms / VSWR: 2:1max
Input power	+10 dBm max.
RF input connector	Type N fem. (front or rear panel) – other connector type on request
RF output connector	Type N fem. (front or rear panel) – other connector type on request
Safety interlock	Connector type BNC
Digital control	Transistors, power supplies, temperatures and fans
Communication interfaces	Ethernet, USB, GPIB, RS232
Color LCD Display with touch screen	Status, faults, (direct and reverse instantaneous power for DC version)
Ambient operating temperature	0 °C / + 35 °C
Room temperature storage	-20 °C / +70 °C
Cooling	Forced air with fan speed control (for D version): 120 l/sec max. (self contained fans)
Power voltage	200-250 VAC, 47-63 Hz, single phase
Rated current	7.4 A at 230 VAC
Dimensions	640 x 840 x 312 mm (7U) / 25.2 x 33.1 x 12.3 in (7U)
Weight	44 kg / 97 lb

230V x 7.4 A = 1.7 kW => 30% efficiency

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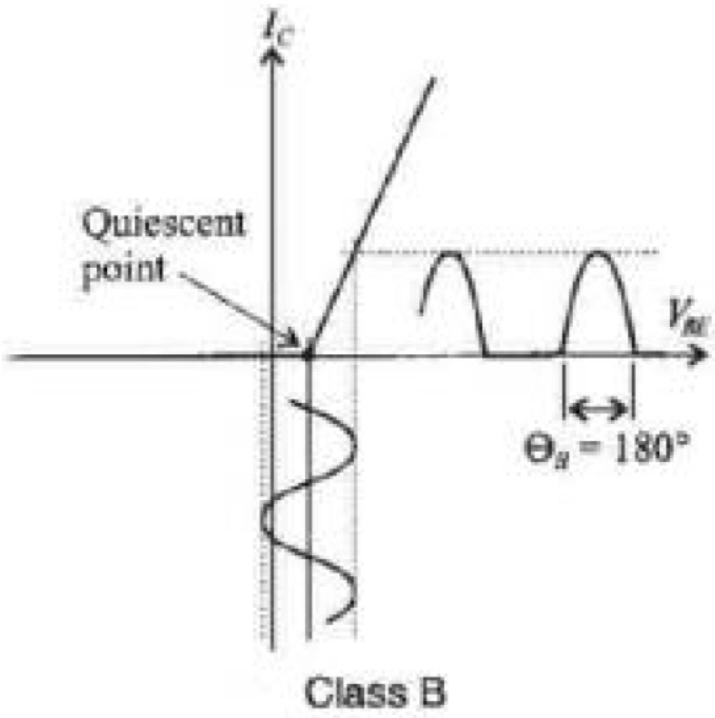
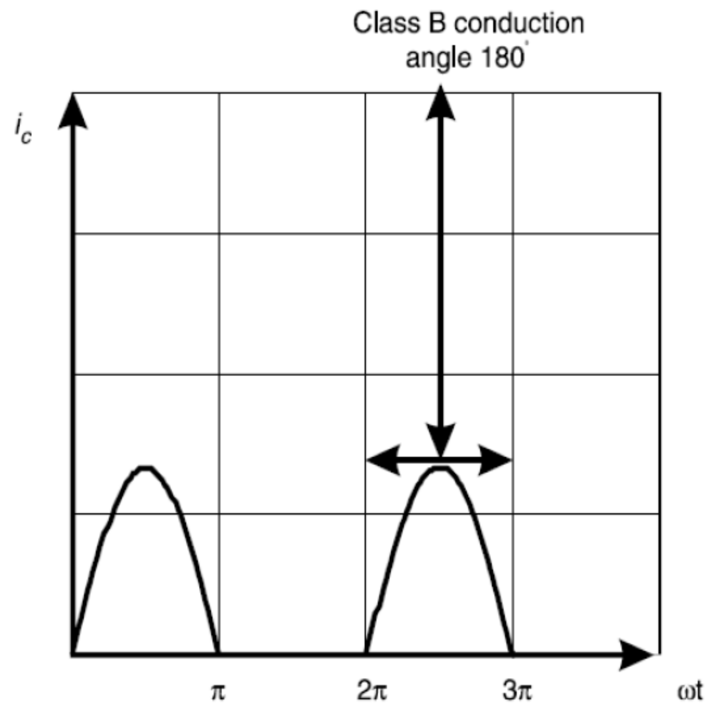
Class B amplifier

Amplifier is biased so that only top half of the signal is amplified.
Harmonics are then filtered out to generate a perfect sinusoid





Signal will look even worse because it is not two linear regions….

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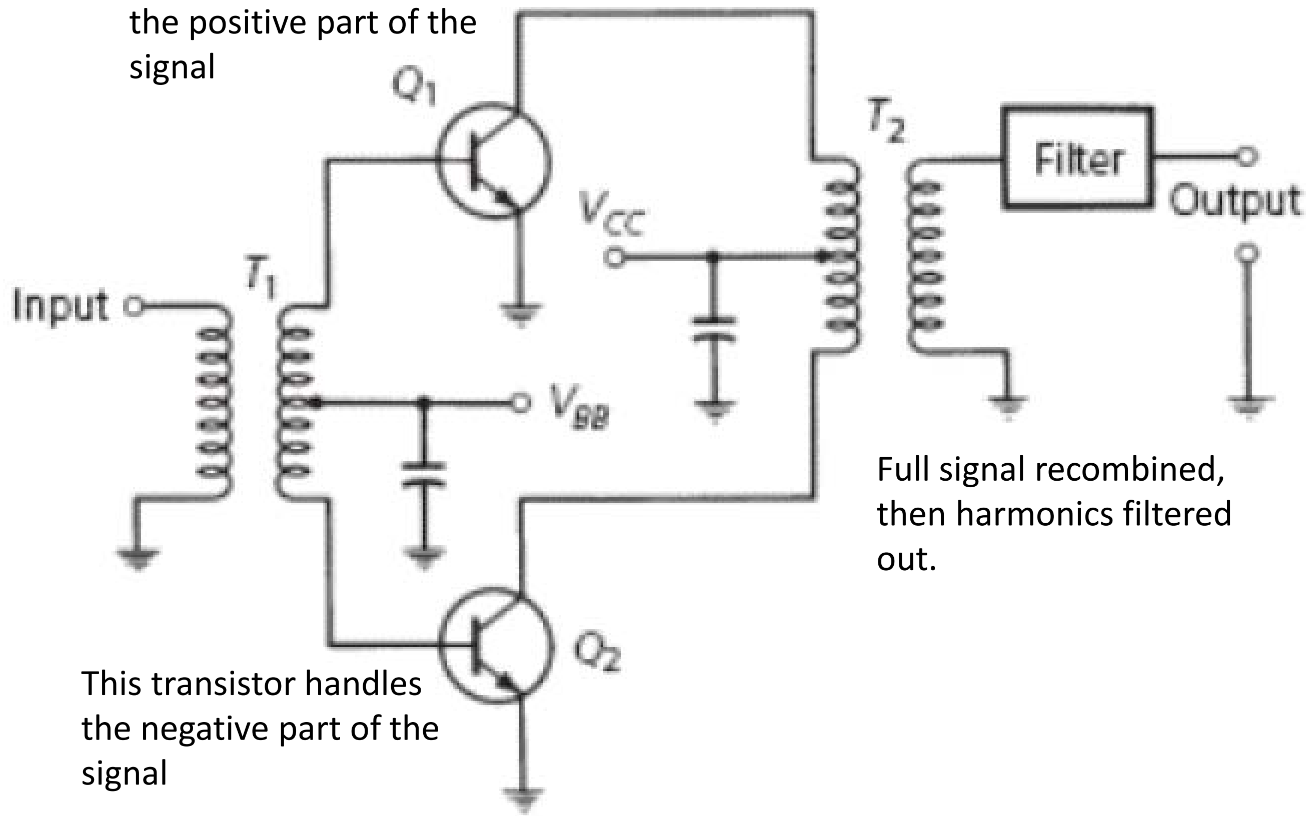
Push-pull Class B amplifier

This transistor handles the positive part of the signal



Full signal recombined, then harmonics filtered out.

This transistor handles the negative part of the signal

Can compensate a little by using push-pull configuration
Both transistors are off when signal is 0.

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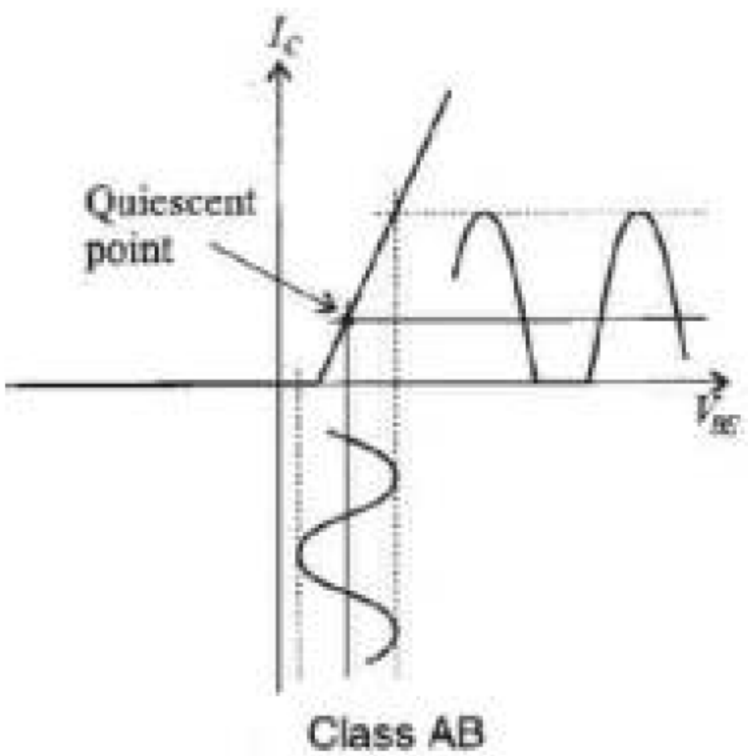
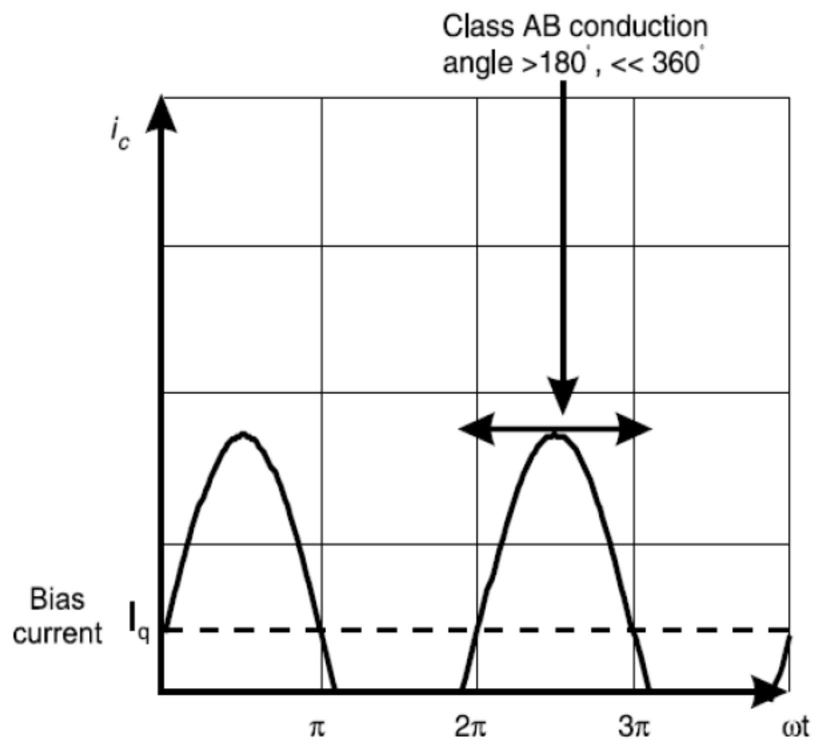
Class AB Amplifiers

Quiescent point is a little higher, still generated harmonics to be filtered out





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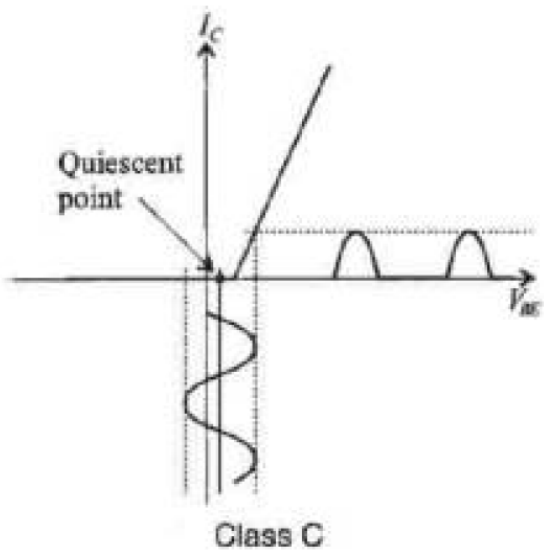
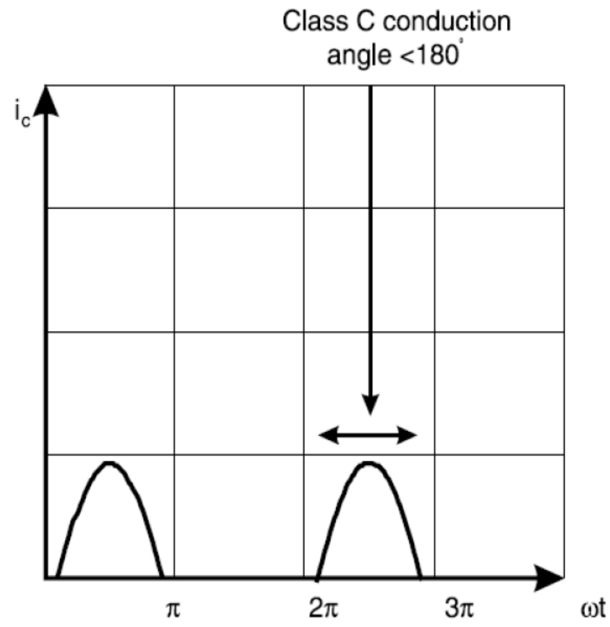
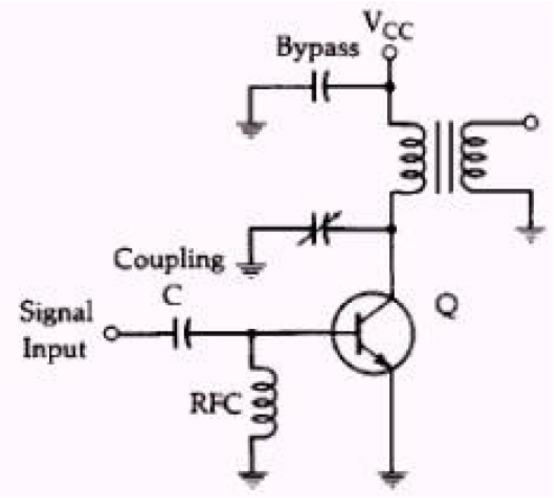
Class C Amplifier

Biased well below zero-crossing of signal
Circuit to bias the input can be very simple
Filtering done with transformer/capacitor pair







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Dis/Advantages of Classes AB/B/C

Advantages

- Transistors are off when no signal applied

Disadvantages

- Filtering required limits operation to a small range of frequencies
- Power consumed within amplifier (in transistors) is still V I

- Can we design an amplifier where the VI product for the transistor (over an entire cycle) is zero?

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Class D Amplifiers

Instead of just amplifying a sinusoid, use transistors as switches to route current
Advantage is that FETs can be designed to be conducting when voltage is 0.

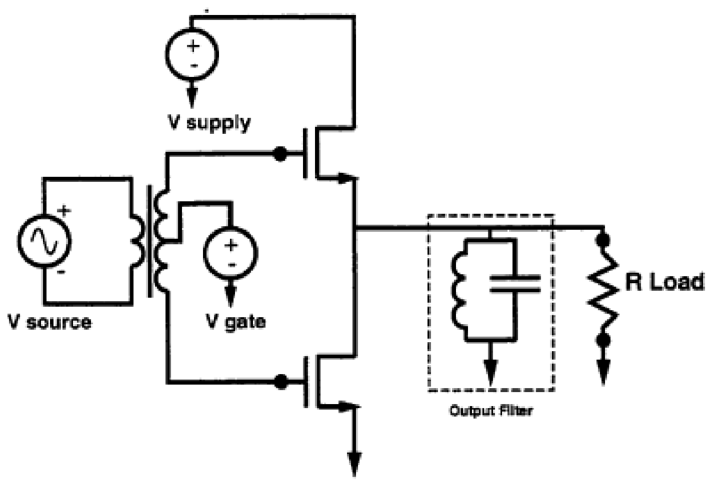
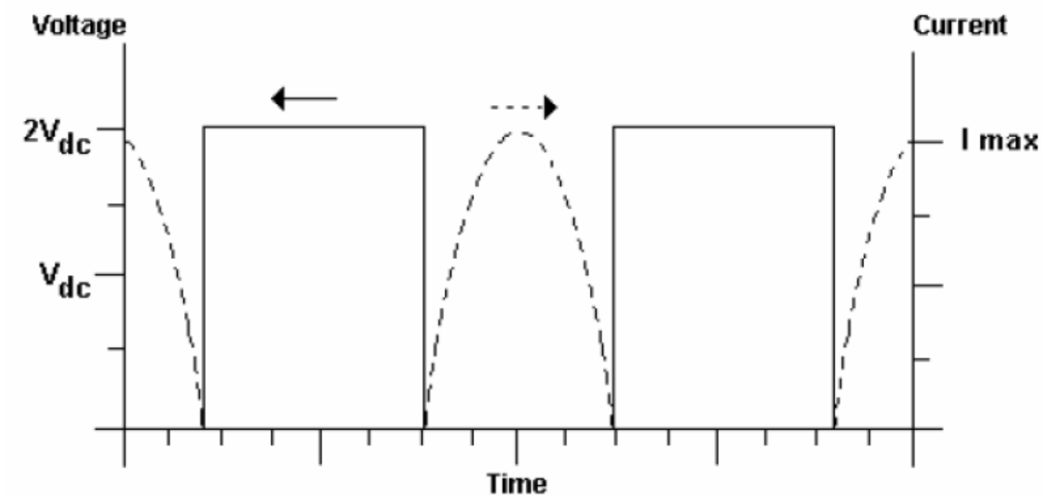


Figure 1.5: Class-D Amplifier



Class-D amplifier

Class-D Voltage and Current waveforms

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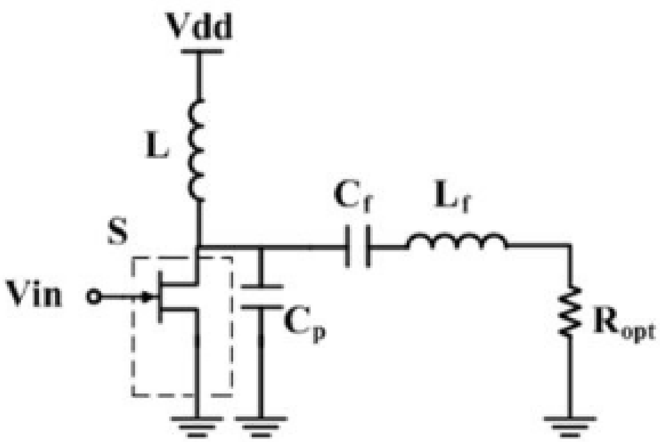
Class E Amplifiers

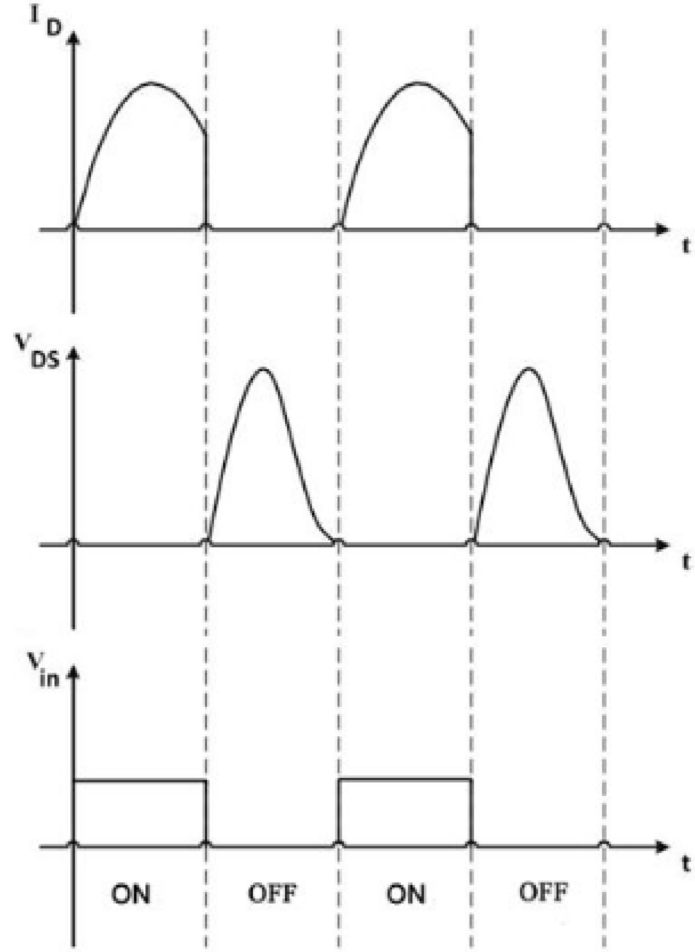
Even more efficient



Soft Switching Properties:

$$V_{DS}\Big|_{t_{ON}} = 0$$

$$\frac{dV_{DS}}{dt}\Big|_{t_{ON}} = 0$$



Classical Class-E Power Amplifier Topology

Class E Amplifiers

Transistors only absorb power during very short periods of the cycle.
Almost all power used goes to output
Lots of harmonics to filter out
Very low component count means higher reliability

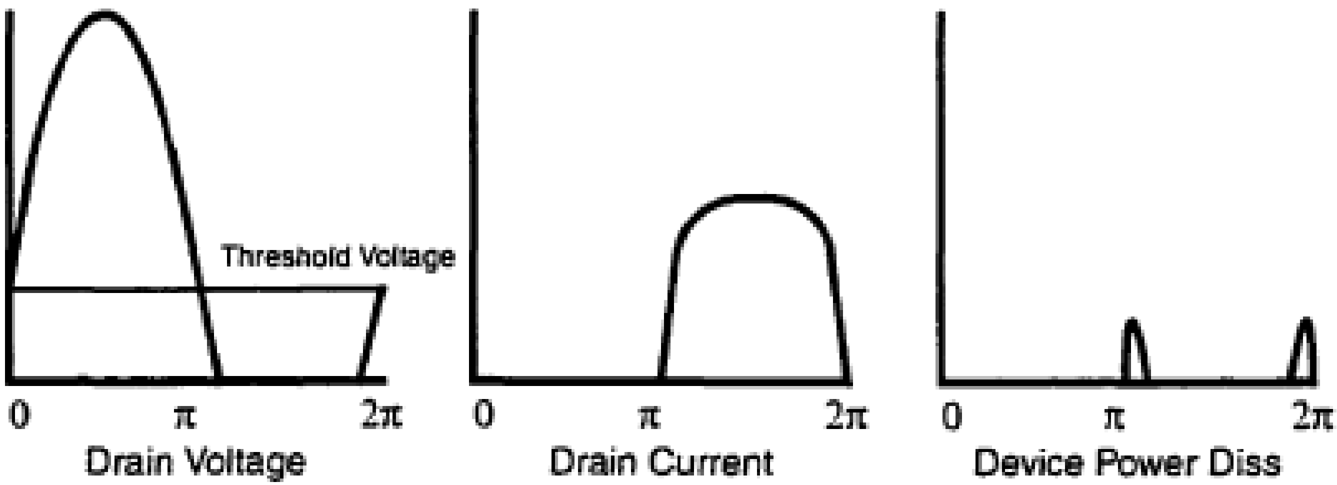


Figure 1.6: Class-E Amplifier Waveforms

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Summary – Amplifier/Source Classes

- Class A
- 30-100 € / Watt RF
- Inefficient but very flexible
- Very linear over a large range

- Class AB/B/C
- Transistors are off when no signal applied
- Distortion so single frequency (narrow band)
- More efficient

- Class D/E
- 5-10€ / Watt RF
- Very efficient
- Narrow band (must filter out all harmonics) and designed for one frequency

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Summary – RF Power Sources

- Frequencies of operation
  - ITU/STM Frequency bands for RF plasmas
  - Amplifiers vs Power Sources
- Input and Output Power
  - Expected impedance and matching
  - Gain compression
  - Harmonics (THD and dBc)
- Classes of Amplifier
  - Class A – Wideband amplifier
  - Classes B to E – Narrow band

Sources

RF Power Amplifiers, Iulian Rosu (qsl.net)

RF Power Amplifiers, Analog Devices Presentation (2003)

RF Circuit Design, Second Edition Christopher Bowick

R. Kubowicz, « Class-E Power Amplifier », Master’s Thesis, University of Toronto 2000.

Wikipedia…

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