DESIGN CONSIDERATIONS

FM TRANSMITTERS

Overview

- Design Criteria
- TX Block Diagram
- VHF Issues
- RF Amplifier
- Harmonic Filter
- Combiner
- Exciter
- Power Supply
- Circuit Board
- Cooling
- Protection

Design Criteria

Early conceptual design starts with knowing a desired RF output power and knowing the Regulatory Requirement governing the broadcast signal such as:

- CE RED (ETSI 302 018, ETSI 301 489-1, EN60215)
- FCC CFR47 Part 73
- Innovation, Science and Economic Development Canada BETS6

These regulations govern items such as occupied bandwidth, spurious and harmonic emissions, Audio quality, AM noise, FM noise, Electro-magnetic compatibility, safety.

Design Criteria

Other design considerations include:

– Reliability

– Redundancy

– Dollars per watt ($/W)

– Power density (W/in^3)

– Power conversion efficiency (operating cost)

– Feature set

These considerations can quite often conflict with each other such as redundancy and $/W.

Designers must understand and choose their guiding principals

Design Criteria

Nautel has always considered reliability one of the leading design principal and as such has an internal engineering document guiding our acceptable component stress.

Electrical stress, at its essence comes from two parameters:

– Voltage (Joules/coulomb) stress causing dielectric breakdown and dielectric heating

– Current (Coulombs/second) stress causing excessive heating of conductors ($P = i^2 R$)

Design Criteria

Examples of Nautel design guidelines include:

- Resistors not to dissipate more than 50% of manufactures rating
- Capacitors operating voltage to be 66% of rating
- Voltage stress in air to be 5V/mil (breakdown at sea level occurs at 75V/mil in a uniform field)
- Transistor junction temperature not to exceed 75% of max rating under normal operating conditions

These guidelines have helped establish a history of highly reliable transmitters.

Design Criteria

Reliability and redundancy have also greatly influence Nautel designs. Going back to our roots, it was a request for improved MTBF that drove the first solid state designs as the Nav Canada needed ultra reliable transmitters in northern Canada which tube designs of the day could not meet.

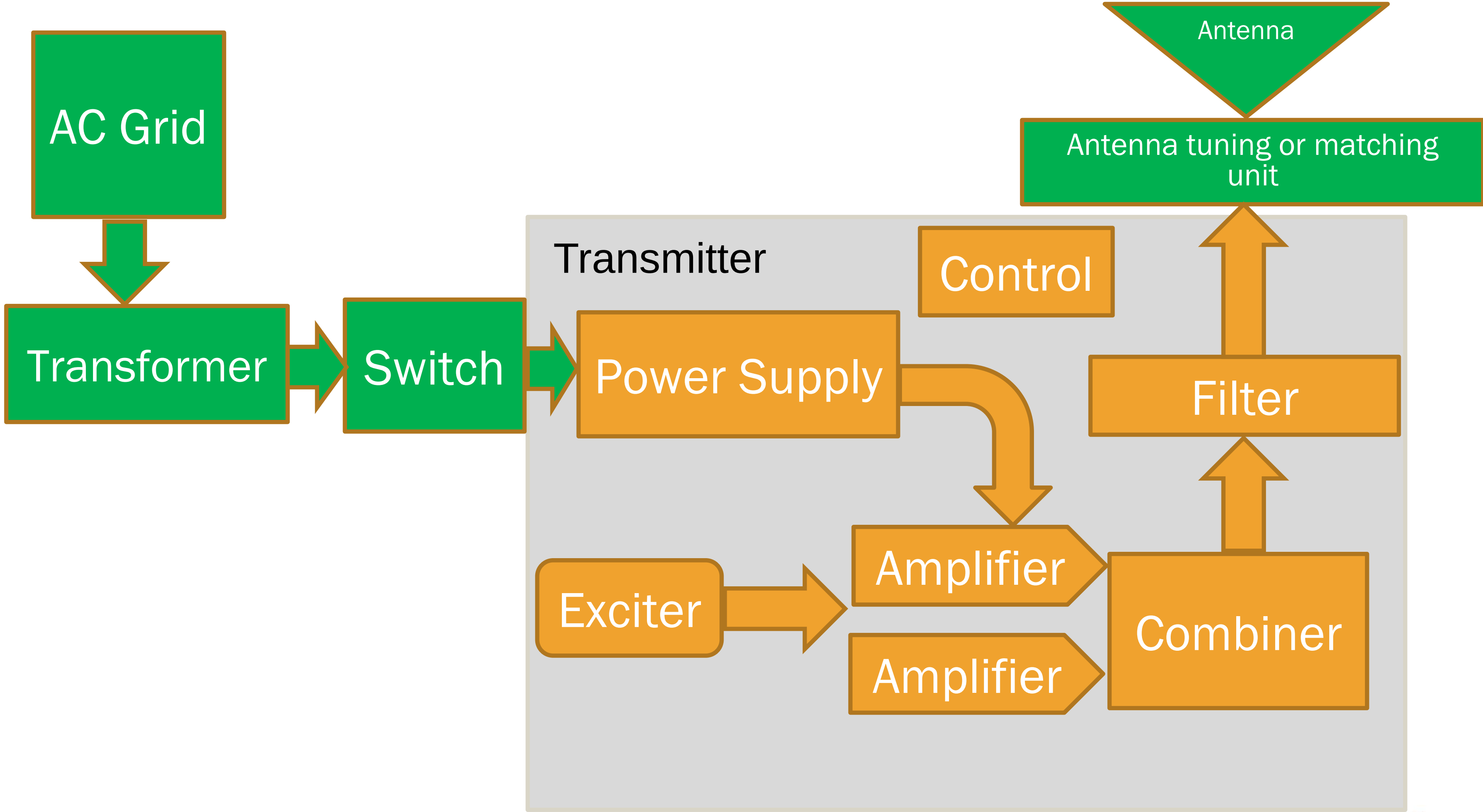
Design Criteria

We continue to build the majority of our design redundancy in mind including:

- multiple parallel amplifiers that can be hot serviced
- dual exciters
- dual low voltage power supplies
- Multiple parallel cooling fans

Generic Transmitter Block Diagram

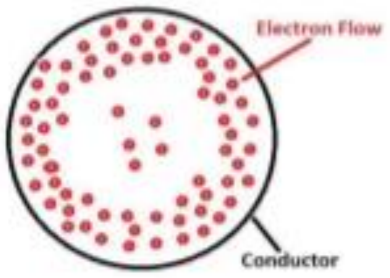
Most transmitters fit the model to the right



VHF Issues

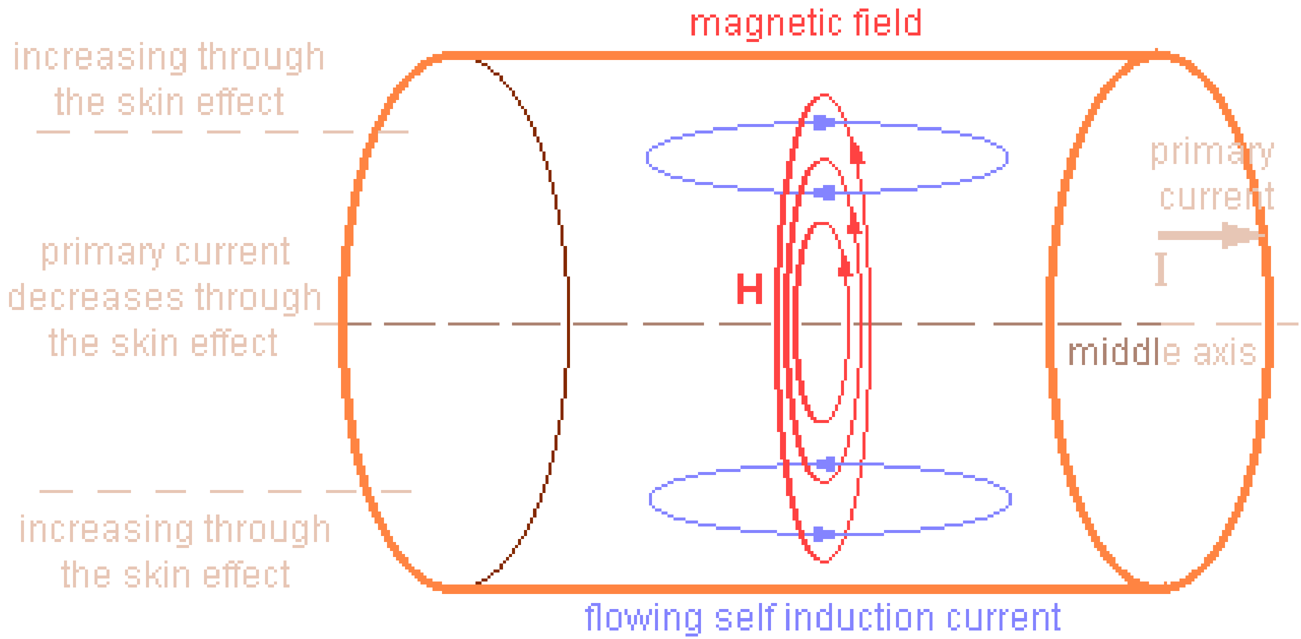
What is Skin Effect?

- **Skin effect** is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor.



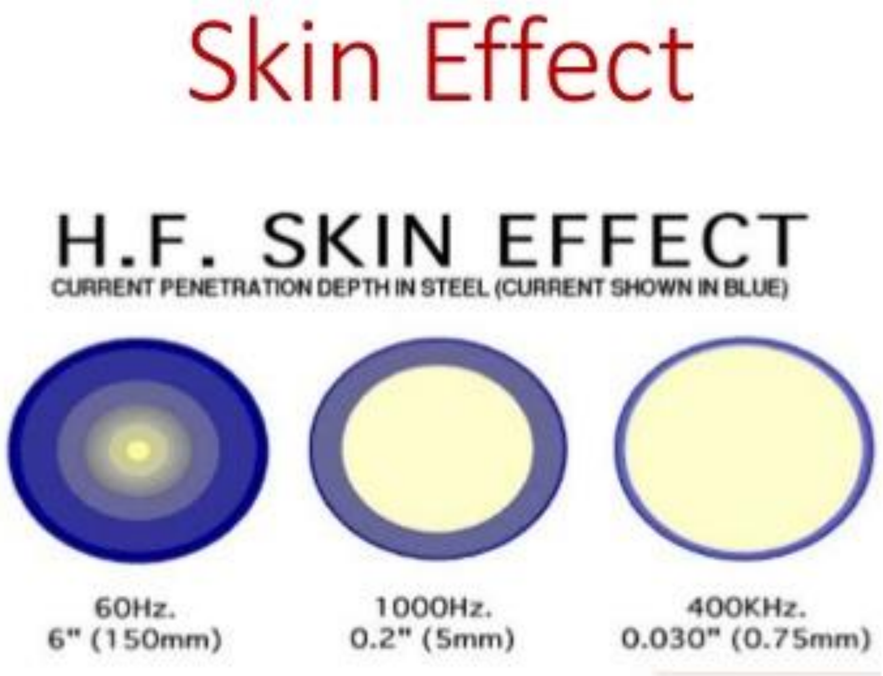
VHF Issues

Skin effect cause AC current to flow on the outside of a conductor



VHF Issues

Skin depth at 100MHz is 0.00025”.



VHF Issues

Skin depth is proportion to $1/(\text{frequency})^{1/2}$

Formula For Skin Depth

We can derive a practical formula for skin depth as follows

$$\delta = \sqrt{\frac{2\rho}{(2\pi f)(\mu_0 \mu_r)}} \approx 503 \sqrt{\frac{\rho}{\mu_r f}}$$

where

ρ = resistivity of the conductor

ω = angular frequency

μ_r = relative magnetic permeability of the conductor

μ_0 = the permeability of free space

VHF Issues

Parasitics are more influential at higher frequencies:

- Lead inductance
- Shunt capacitance

- Resistors self resonate at VHF and become high impedance

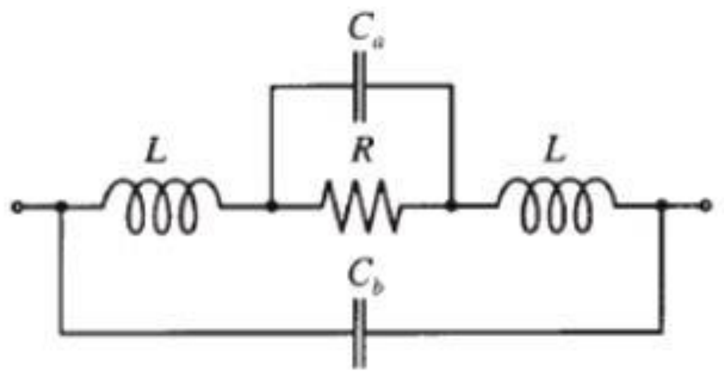


Fig: Electric equivalent circuit representation of the resistor

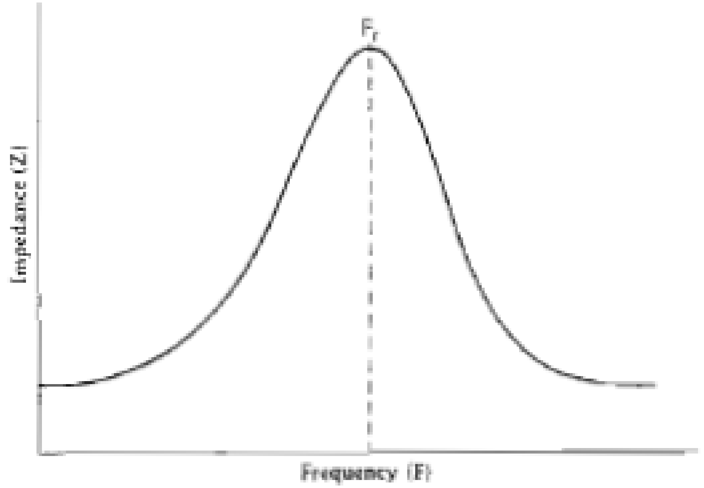


Fig. 1-3. Impedance characteristic of a wirewound resistor.

VHF Issues

Inductors self resonate at VHF and become high impedance

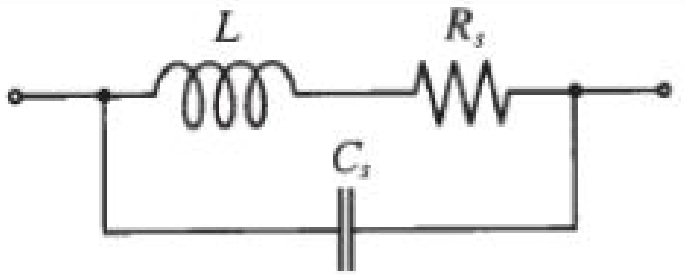


Fig: Equivalent circuit of the high-frequency inductor

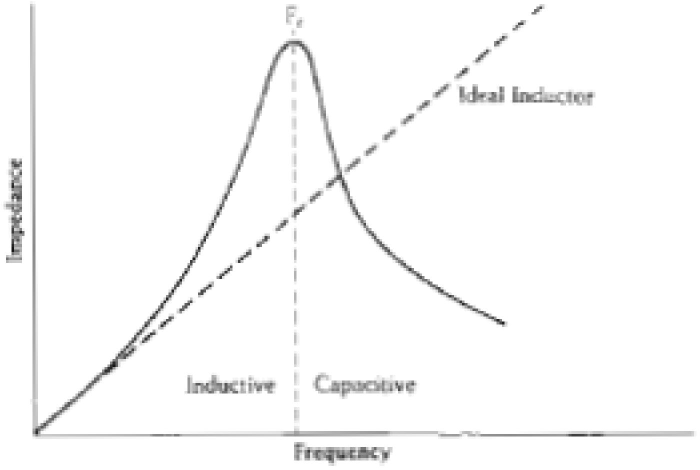


Fig. 1-16. Impedance characteristic vs. frequency for a practical and an ideal inductor.

VHF Issues

Capacitors self resonate at VHF and become short circuits

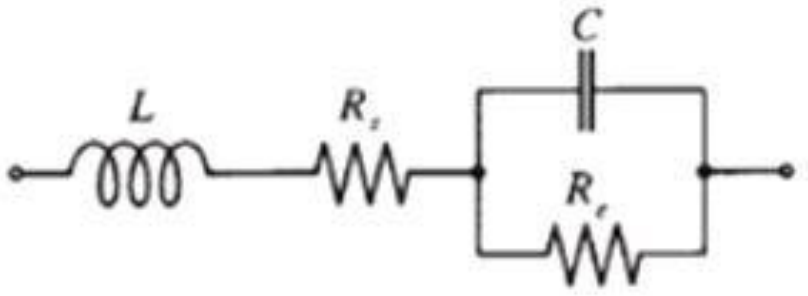


Fig: Electric equivalent circuit for a high-frequency capacitor

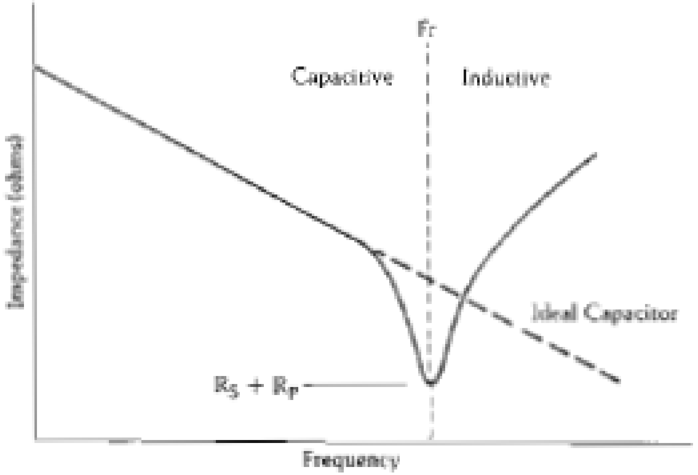


Fig. 1-9. Impedance characteristic vs. frequency.

VHF Issues

Capacitor self resonance curves

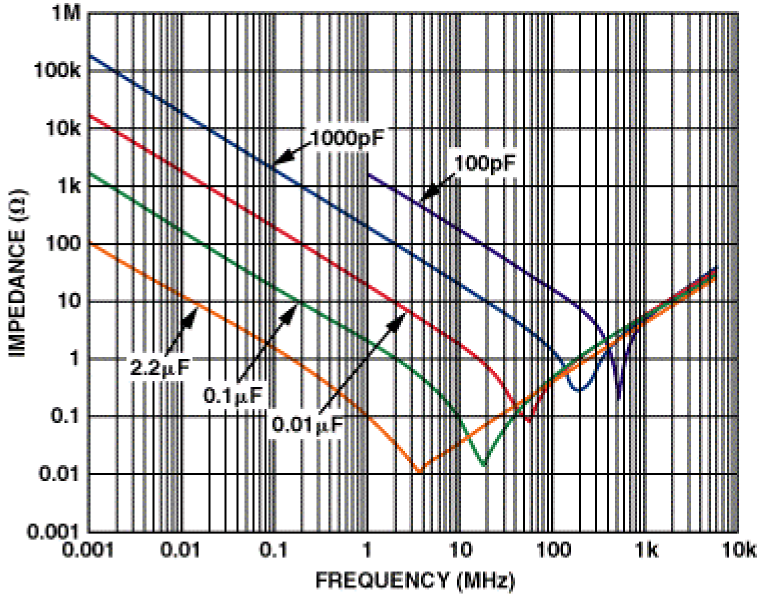


Figure 1. Capacitor impedance vs. frequency.

VHF Issues

Dissipation in FR-4 needs to be reviewed closely as
DF=0.02
DF= 1/Q
For FR-4, dielectric losses are 1/50 of V^2/X_c

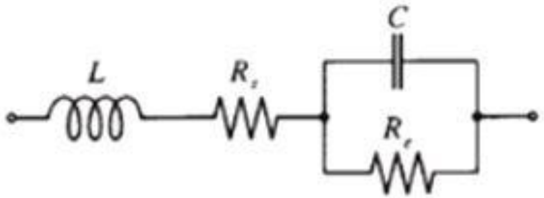


Fig: Electric equivalent circuit for a high-frequency capacitor

Selection of High Frequency Materials for PCB Design

Tier6		Taconic RF35 TLG30	PTFE	RO3000 RO4230 RO4003		Df<0.003
Tier5		Rogers RO4350B	Isola IS640 Speedboard Megtron 6	Arlon FR25		Df~ 0.003~0.005
Tier4		LG 200LL	Nelco N4360 N4000-12	IS625	Hitachi LX67	Df~ 0.005~0.007
Tier3	Megtron 5	N4000-13S N4000-13	Arlon 11N	IS620	IT200DK	Df~ 0.007~0.010
Tier2	Isola FR408 IS415	Panasonic Megtron	Isola Getek & Getek HR	BT	Halegen free FR-4	Df~ 0.010~0.020
Tier1	Standard FR-4	Halegen free FR-4		High Tg FR-4		Df>0.020

Bicheng PCB

RF Amplifier

The RF amplifier design is critical to the transmitter's $/W, W/$\mathrm{in}^3$, efficiency and reliability.

Usually the amplifier will be the building block of a family of models.

The power capability needs to be large enough to minimize combiner and connectors costs but small enough not to drastically affect power capability under failure. Shipping and servicing weights are also very important.

RF Amplifier

Class D amplification cannot switch effectively at VHF.

Therefore other amplifier classes are used.

In the mid 1980's Motorola introduced MRF151G which utilized a dual (Gemini) MOSFET. ($150US each!)

This FET became the became the de faco standard as it allowed for maximum $/W and W/$\mathrm{in}^3$.

RF Amplifier

MRF151G used vertically diffused metal oxide semiconductor (VMOS).

In the early 2000’s a new semiconductor technology was introduced using Laterally Diffused Metal Oxide Semiconductor or LDMOS.

LDMOS Advantages over VDMOS

- TWICE the power per package
- Withstands higher VSWR
- Higher efficiency
- Higher gain
- Lower thermal resistance ($R_{\Theta JC}$)
- Increased ruggedness
- No Beryllium Oxide (dangerous material)

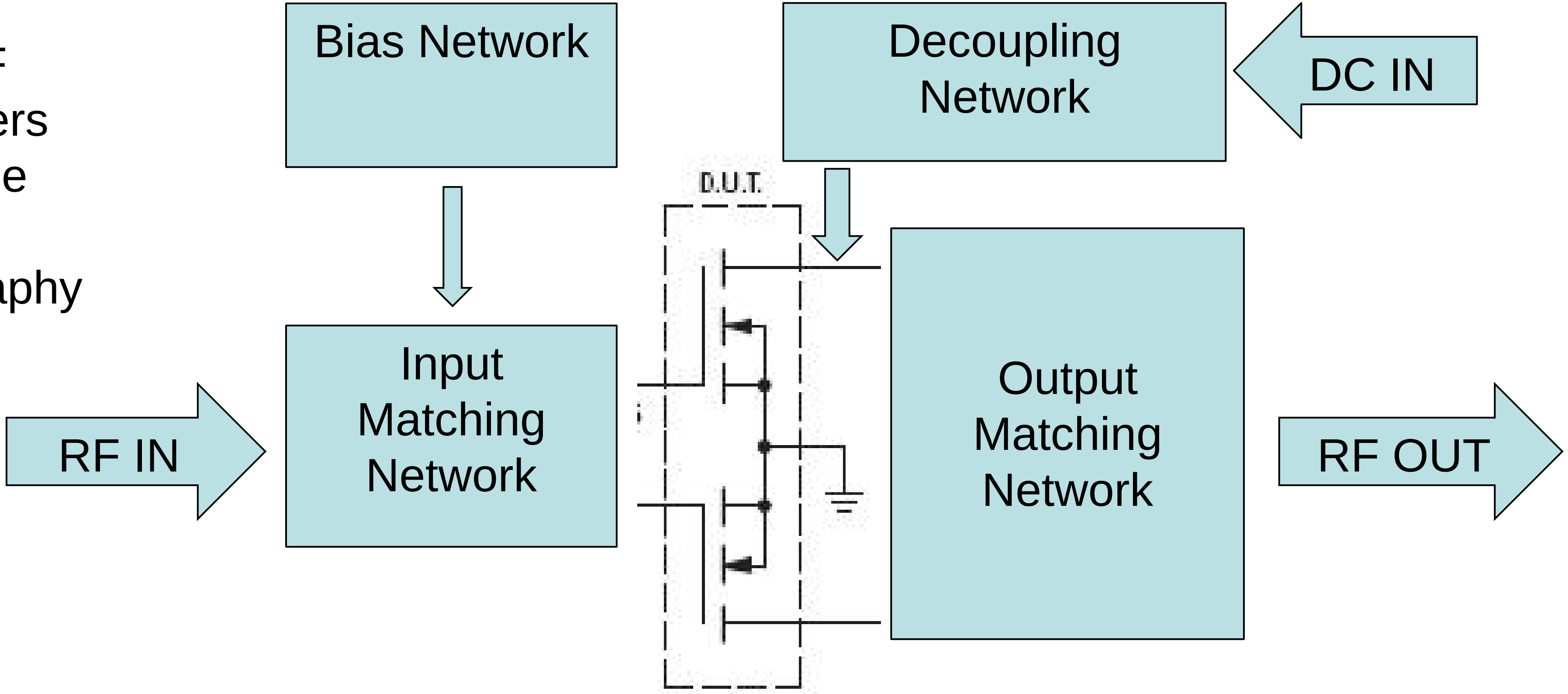
LDMOS Advantages

Implications in Nautel design:

- 4 pallets per PA module in NVLT and GV (was 8)
- No IPA stage in NVLT and GV
- Fewer combining levels
- Higher efficiency spec
- Lower heat load

RF Amplifier

All VHF amplifiers have the same topography



RF Amplifier

Input Matching Network – matches 50Ω driver to FET low impedance input (Gate), unbalanced to balanced

Output Matching Network – matches FET low output impedance (Drain) to 50Ω load, balanced to unbalanced

Decoupling Network – provides a low impedance supply of DC voltage to the FET Drains

Bias Network – provides high impedance supply of DC voltage to the FET Gates

RF Amplifier

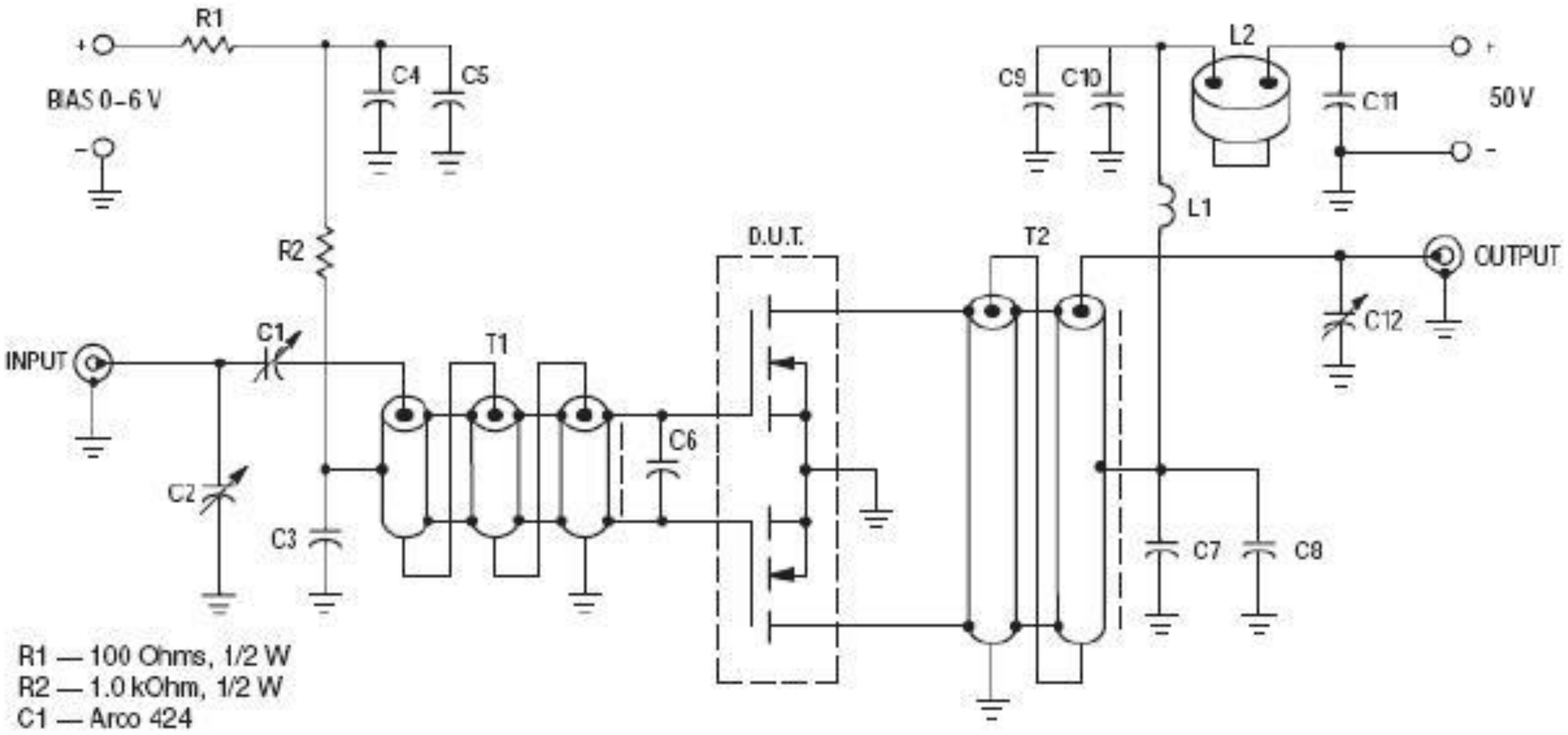
Amplifier efficiency is affected by 2 factors:

- FET on resistance (i^2R_{DSon})
- Switching loss ($1/2CV^2F$)

Amplifier power capability is limited by:

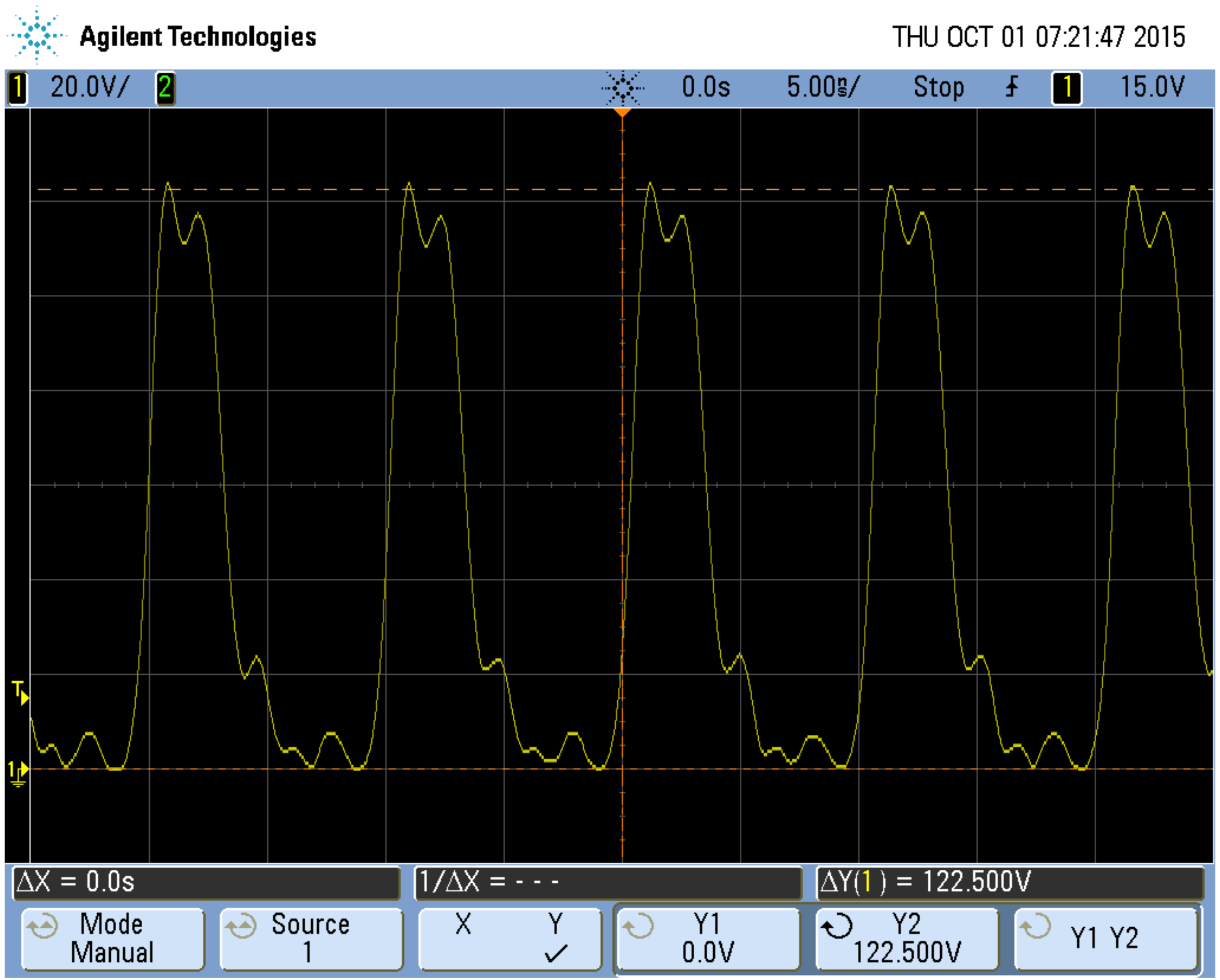
- Peak drain voltage
- Junction temperature

RF Amplifier



RF Amplifier

Drain voltage rings to 2.5 times DC voltage and approaches BVdss. Amplifier output waveform is harmonic rich.



RF Amplifier

Design sequence

1) FET selection determines power supply voltage (PAV)
2) FET selection determines RF power capability of PA
3) Amplifier design determines RF filter requirements
4) Power module design combines PA's
5) TX TPO determines # of RF modules
6) # of RF modules determine # of inputs on combiner

RF Amplifier

Typical values for GV40

1) PAV=50VDC
2) PA power = 750W
3) RF module = 2900W
4) # of RF modules =16
5) Combiner inputs=16

Harmonic Filter

Early FM harmonic filter needed to impedance match the antenna to the amplifier to achieve designed power. ($50\Omega/64=0.78125\Omega$ for Q20)

No matching needed on NV/GV.

The harmonic filter needs to attenuate harmonics produced in the amplifiers.

The harmonic filter needs to provide isolation from external energy which could damage the amplifiers.

Harmonic Filter

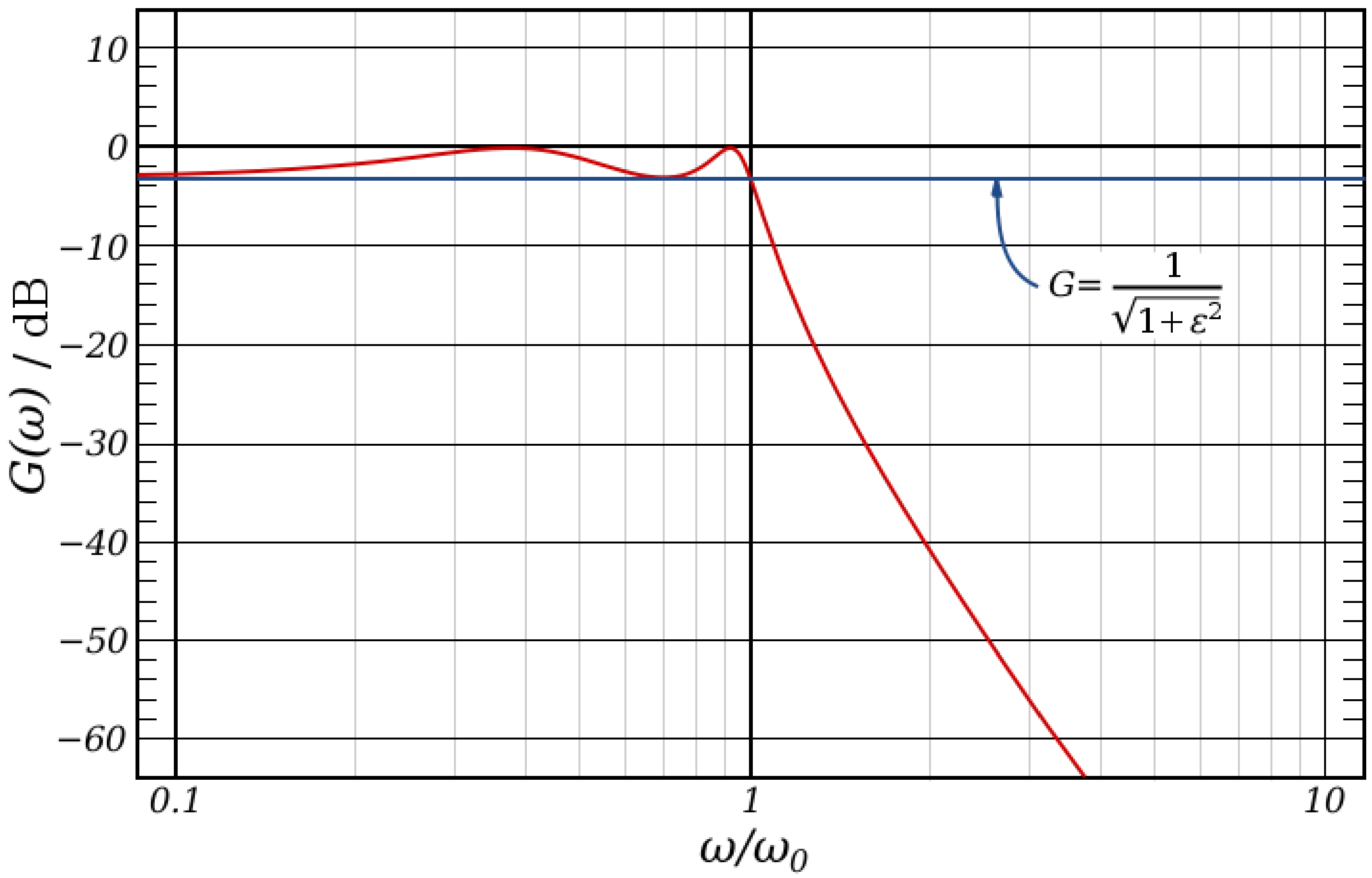
Current FM harmonic filters uses a multi-pole Chebyshev reduce harmonics which includes:

- Wide bandwidth for broadband operation
- Good attenuation of harmonics

A shunt coil provide static and low freq transient protection.

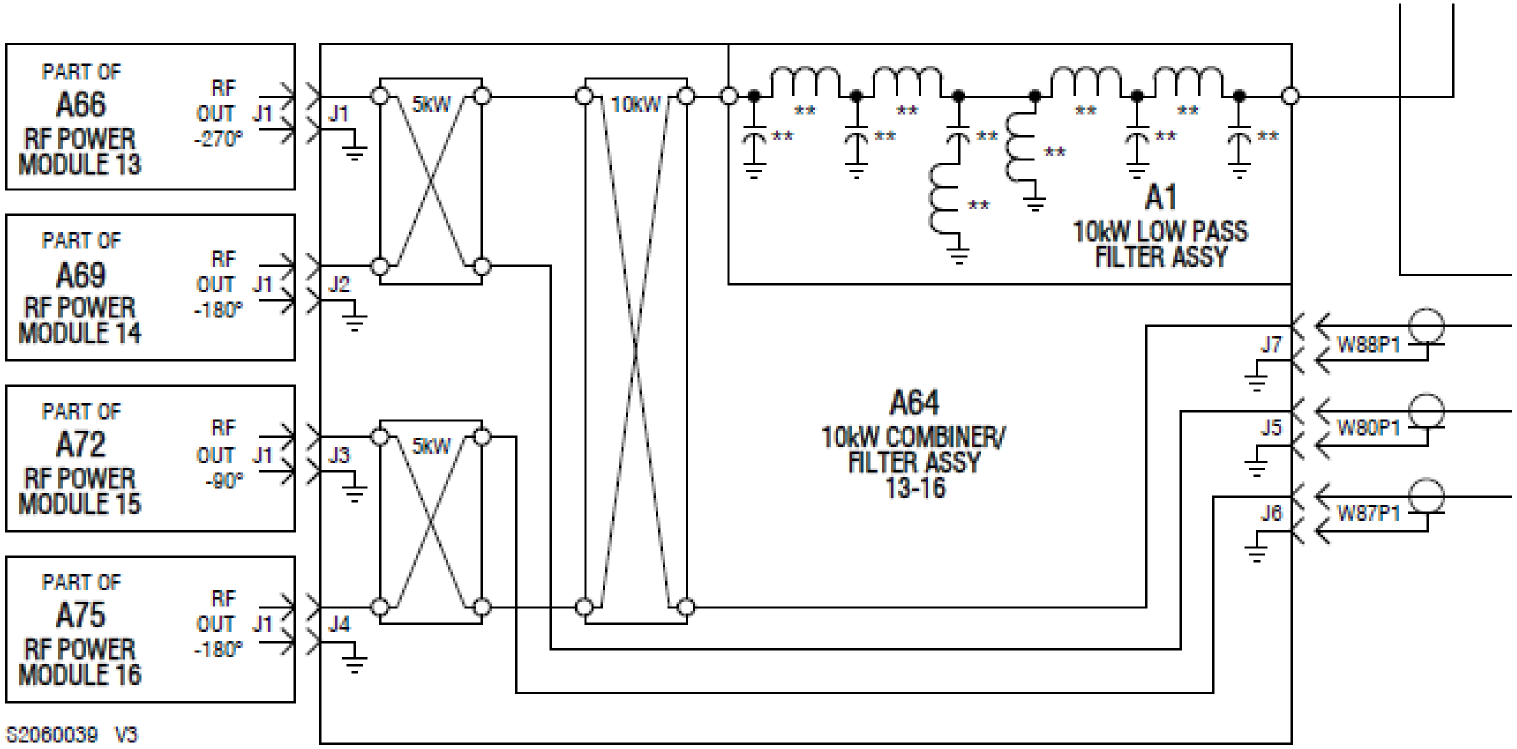
Harmonic Filter

Chebyshev 9 pole low pass with 2nd harmonic notch is used in NV/NVLT/GV. Chebyshev gives acceptable attenuation and smooth passband ripple.



Harmonic Filter

A shunt inductor is placed in the filter to provide a low impedance to ground



Combiner

The combiner needs to efficiently add the RF modules powers while providing isolation between inputs.

Combiners can be categorized as those with balancing resistors and those without.

Number of inputs needs to be greater than 4 for combiners without balancing resistors in ordered for reasonable isolation under failure.

Combiner

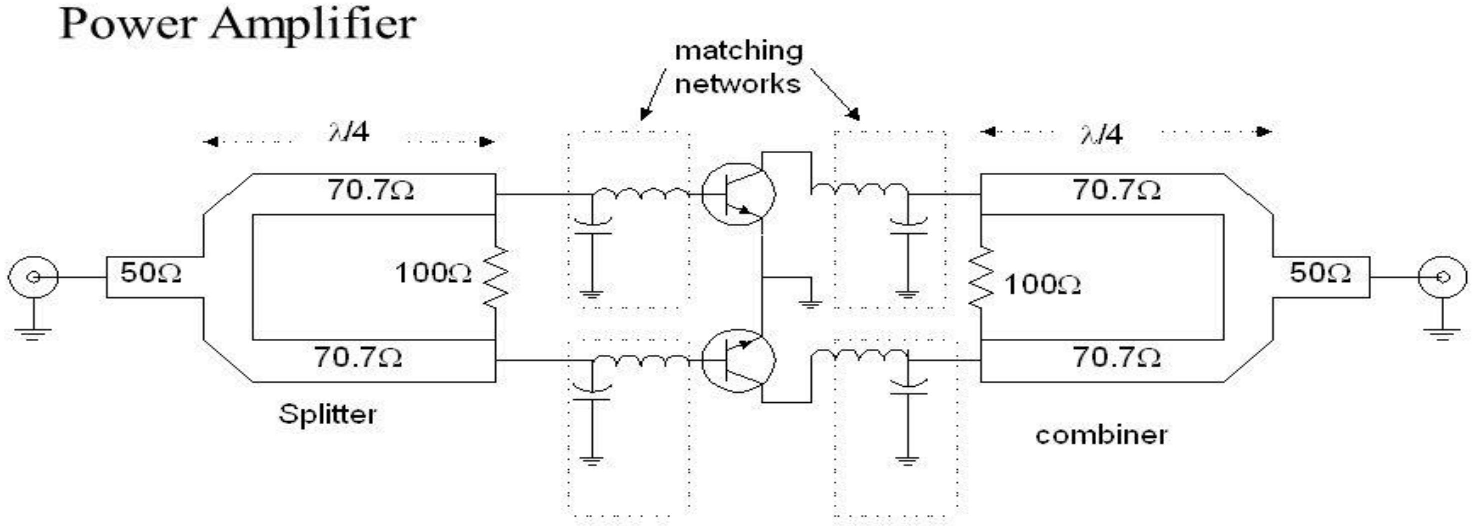
Early FM designs used combiners without balancing resistors.

With the need for broadband operation and IBOC, combiners (and splitter) designs now use mainly 2 types:

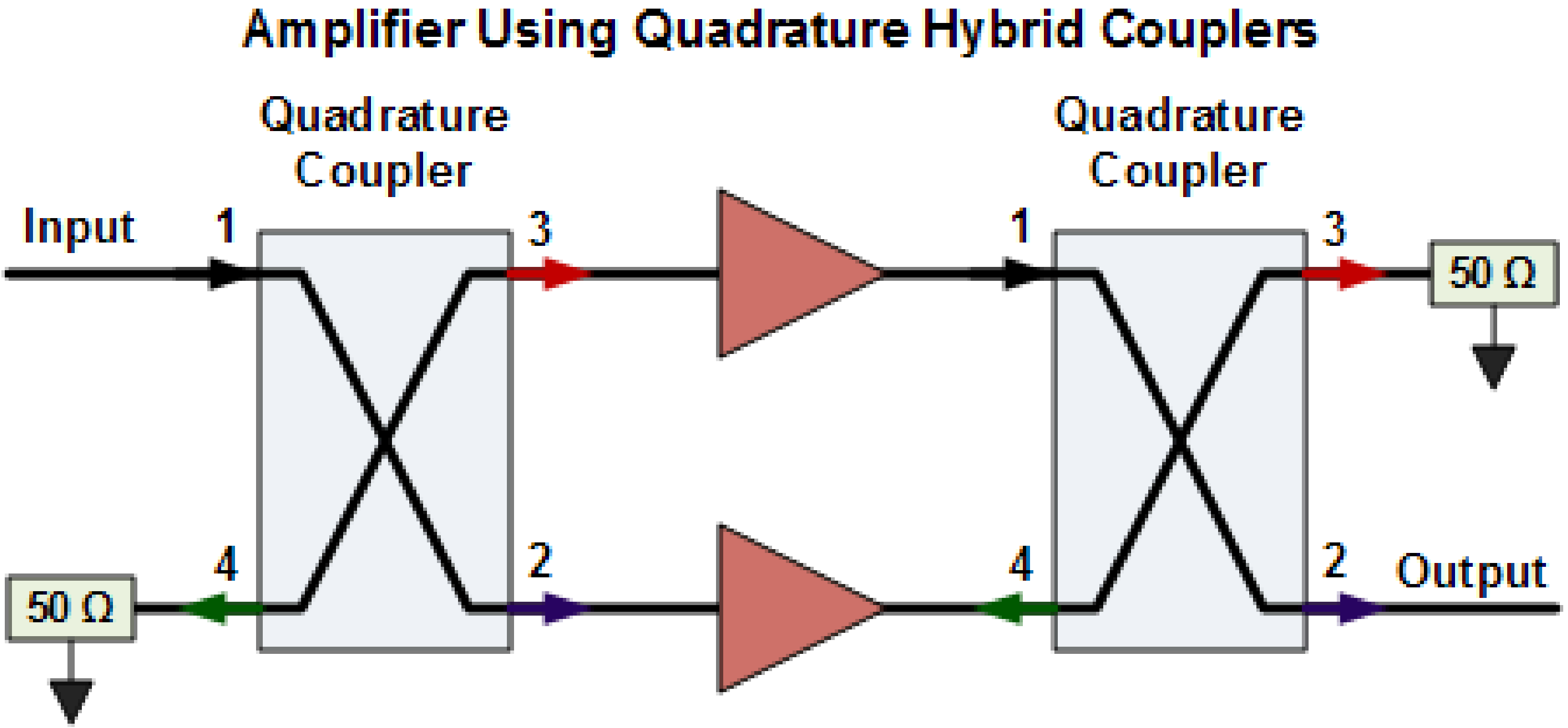
- Wilkinson
- Quadrature 3dB coupler

Combiner

Wilkinson splitter/combiner application

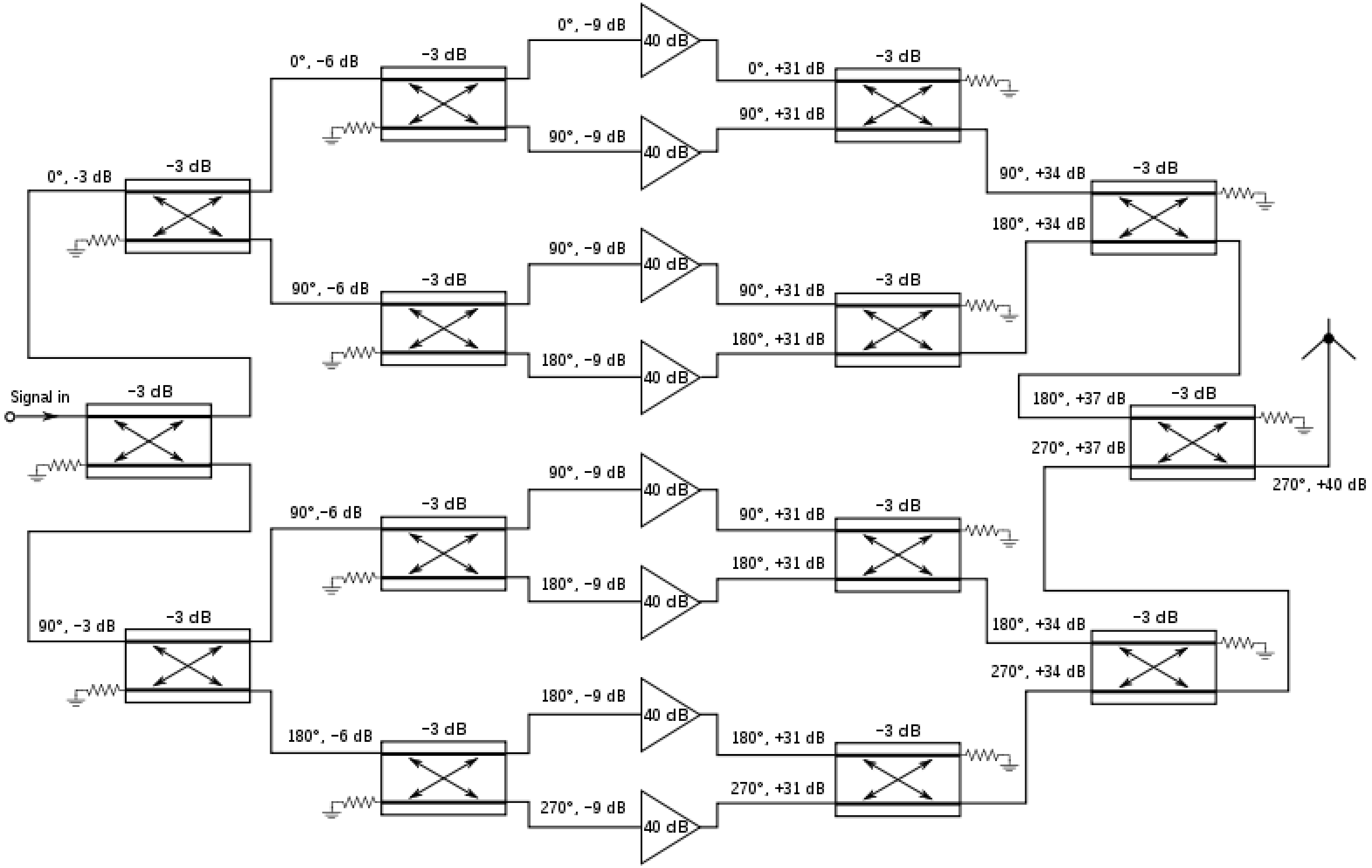


Combiner


Amplifier Using Quadrature Hybrid Couplers
Quadrature Coupler
Quadrature Coupler
Input
1
3
2
4
50 Ω
1
3
4
2
50 Ω
Output

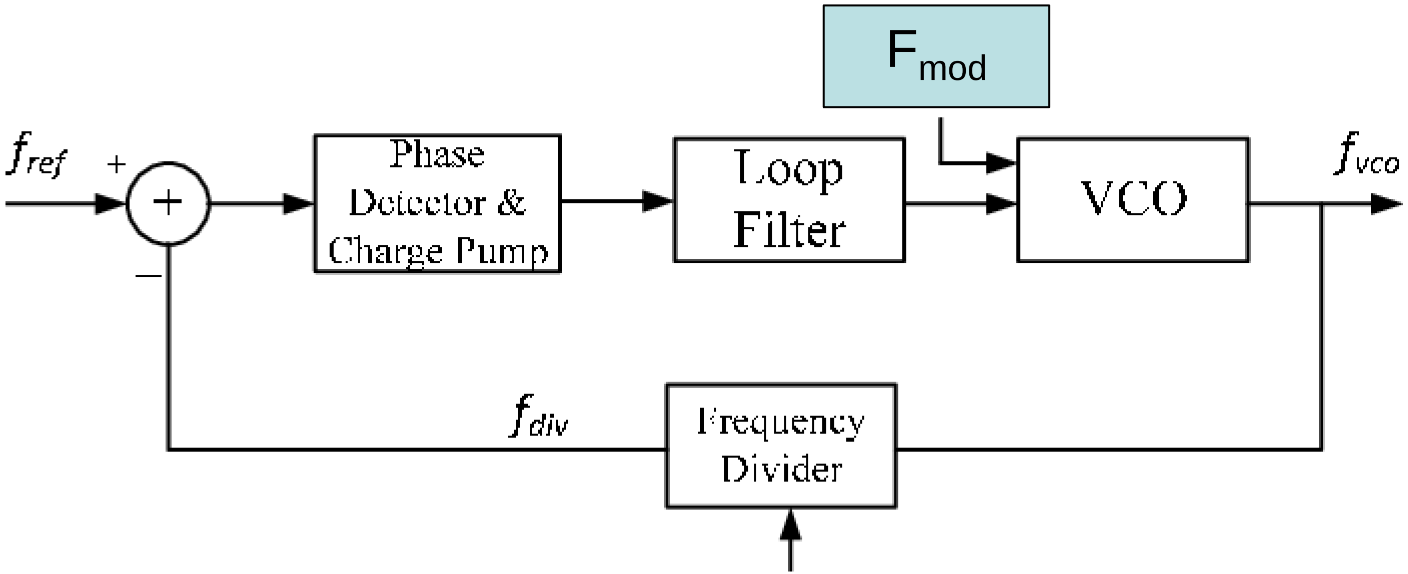
Combiner

Corporate combining using 3dB couplers is used to drive and combine multiple RF sources.



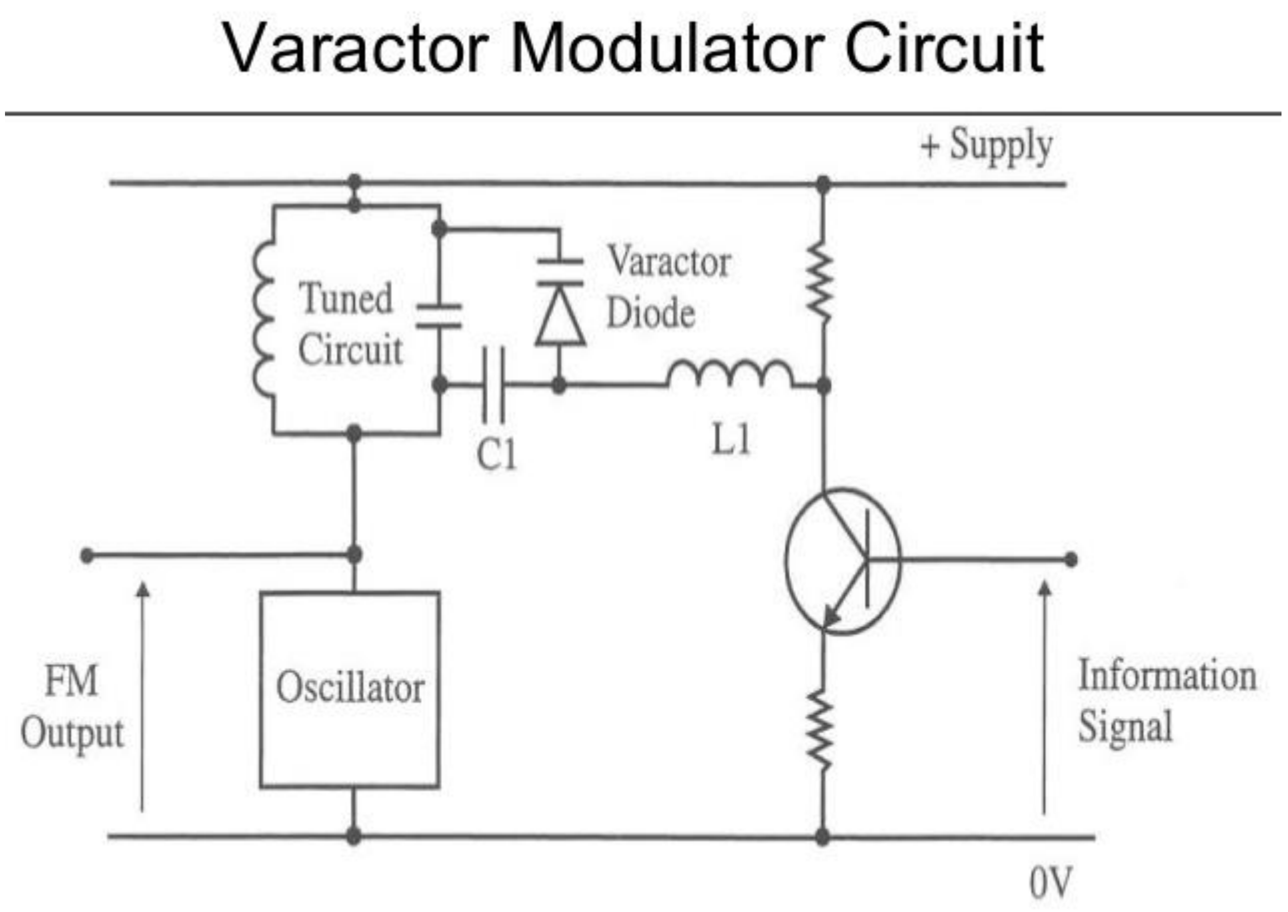
Exciter

Exciter design has advanced greatly from early varactor diode/PLL to a powerful DSP and FPGA.



Exciter

Varactor diode/PLL is non-linear, susceptible to stray fields, unable to reject low frequency noise.



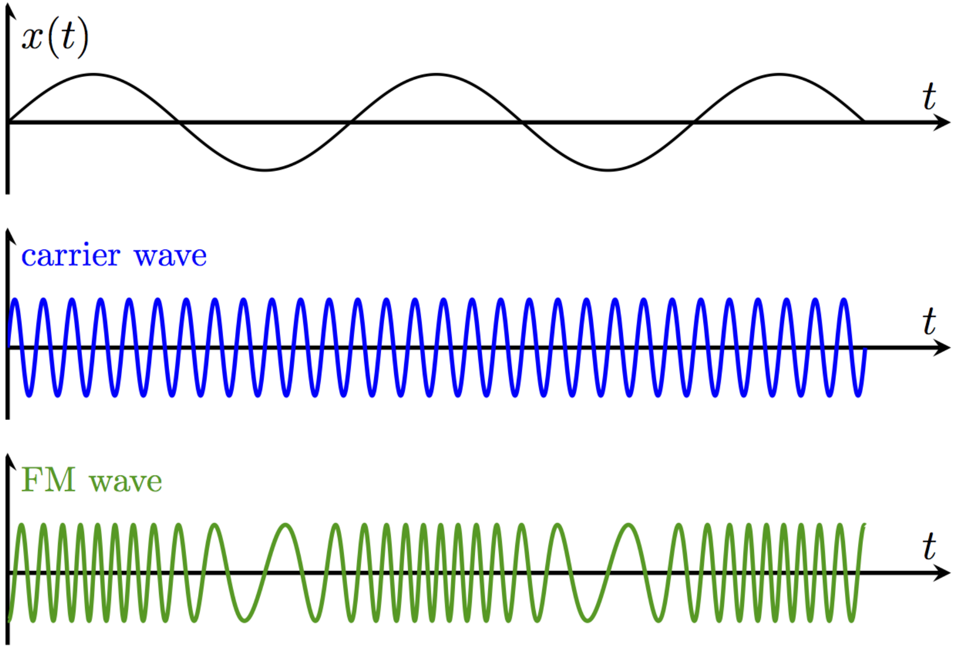
Exciter

Analog FM signal has constant amplitude

Let the modulating signal be $x_m(t) = \beta \cdot \sin(\Omega_m t)$

Let the carrier be $x_c(t) = X_c \cdot \cos(\Omega_c t)$

Then $x(t) = X_c \cdot \cos[\Omega_c t + \beta \cdot \sin(\Omega_m t)]$



Exciter

IBOC added the requirement to amplify amplitude as well as phase information

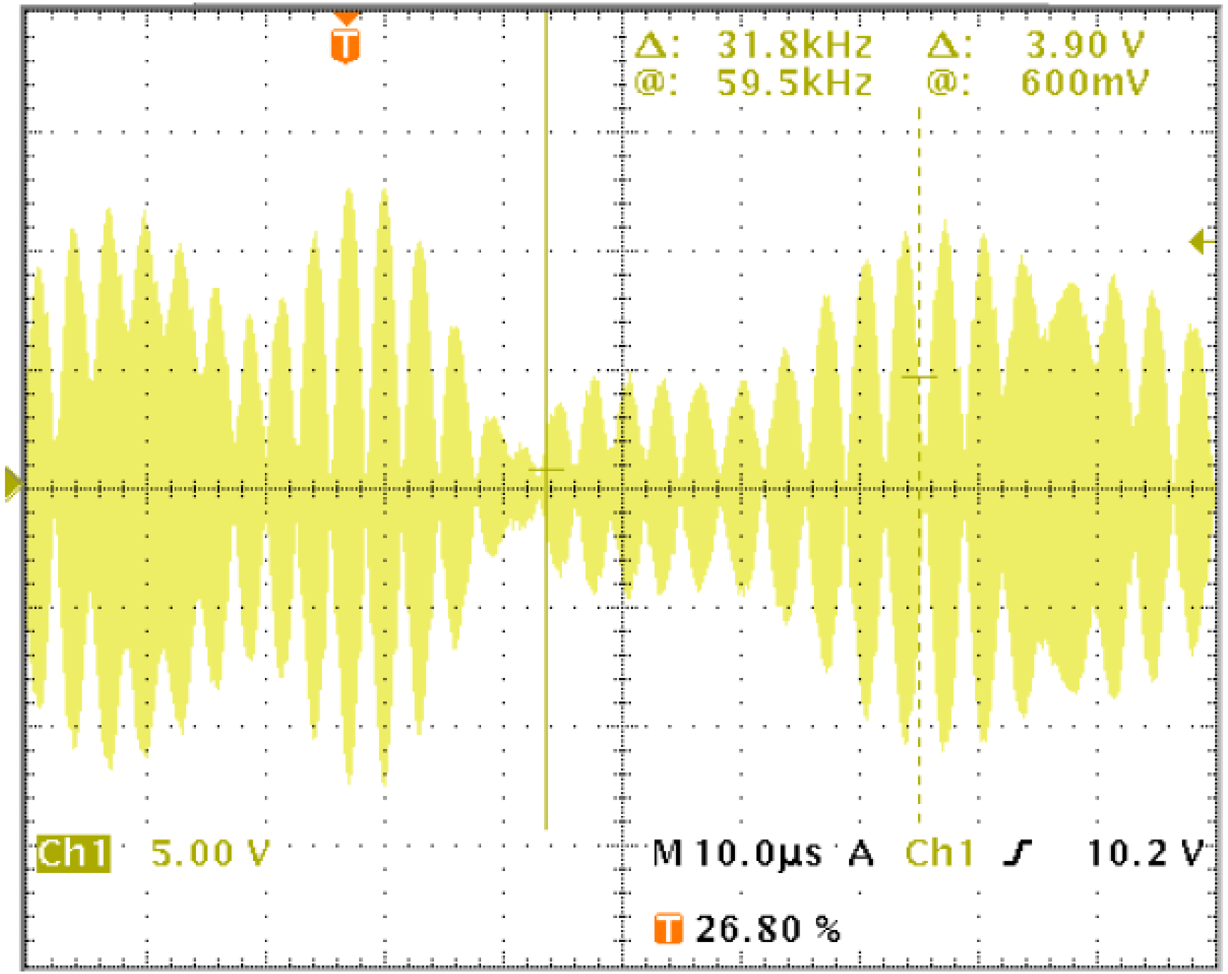
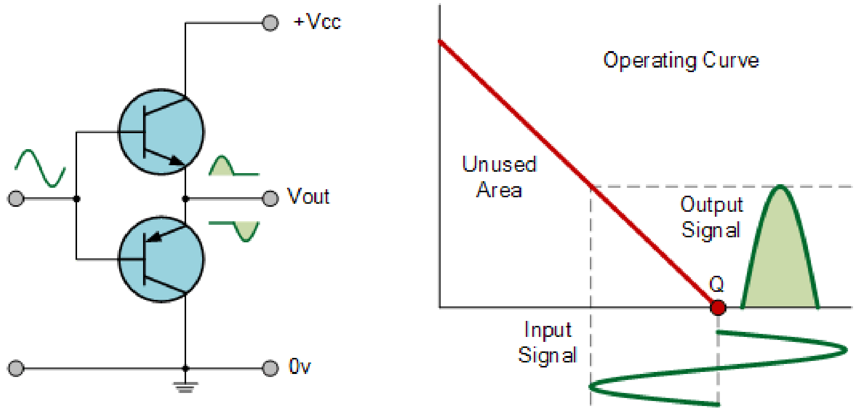


Fig 2 Time Domain of IBOC RF Signal

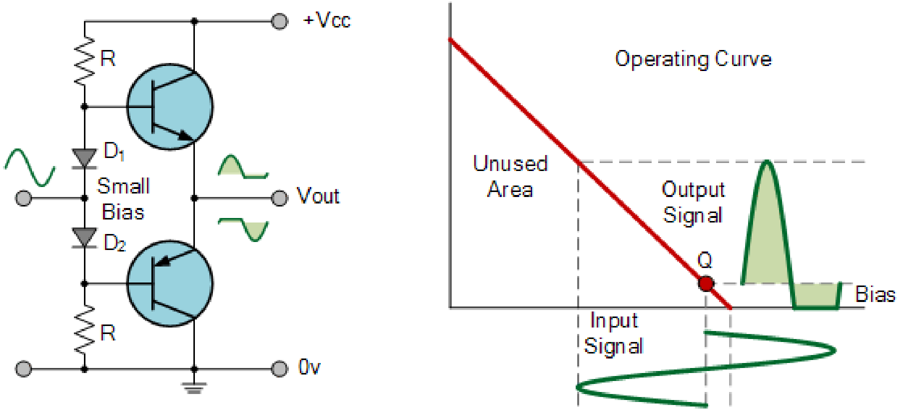
Exciter

IBOC Amplifier needs to be more linear than the analog only predecessors

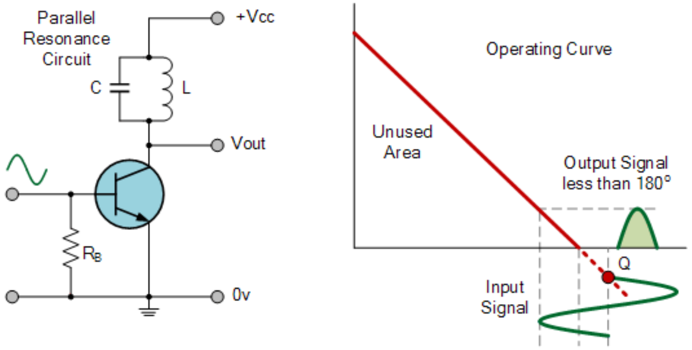
Class B Amplifier



Class AB Amplifier

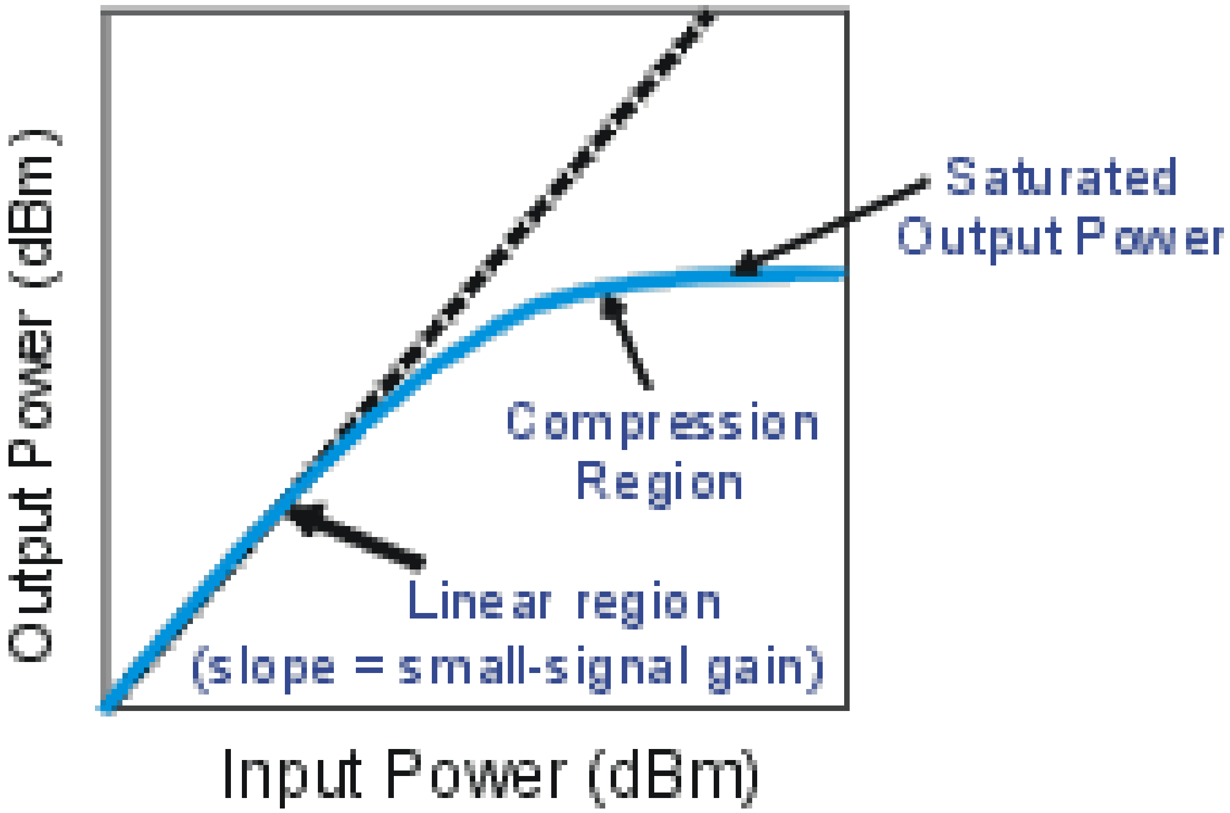


Class C Amplifier



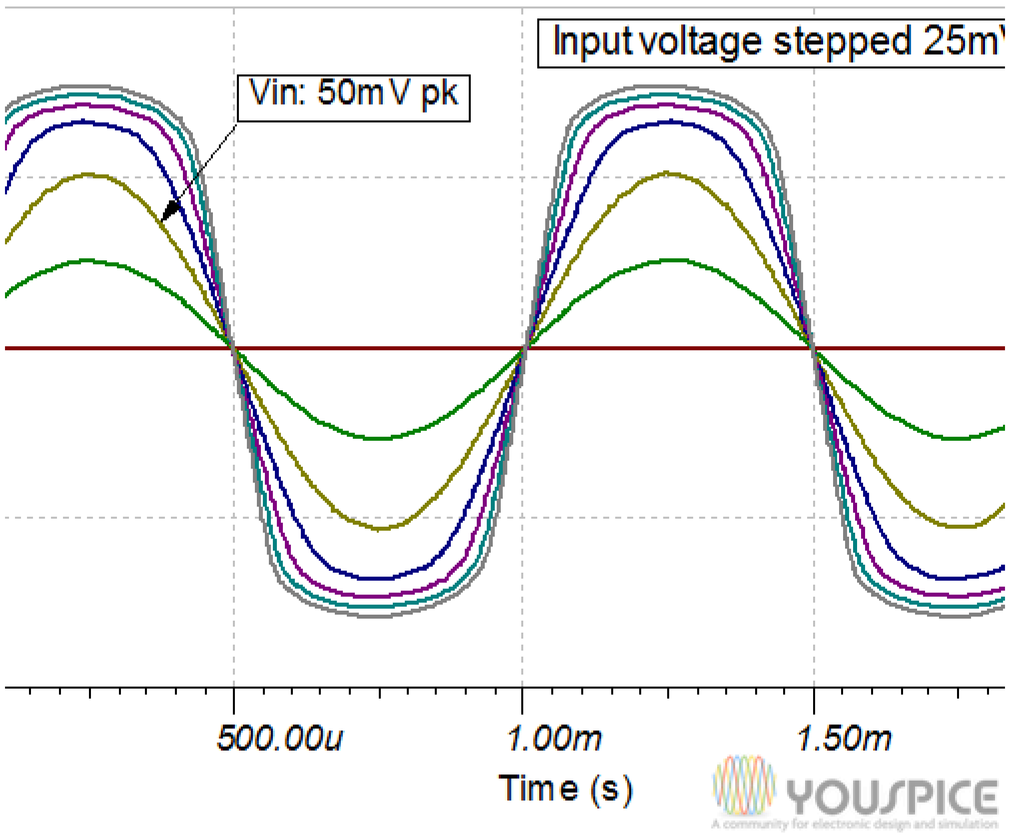
Exciter

Despite adding bias, the RF amplifier is not linear.



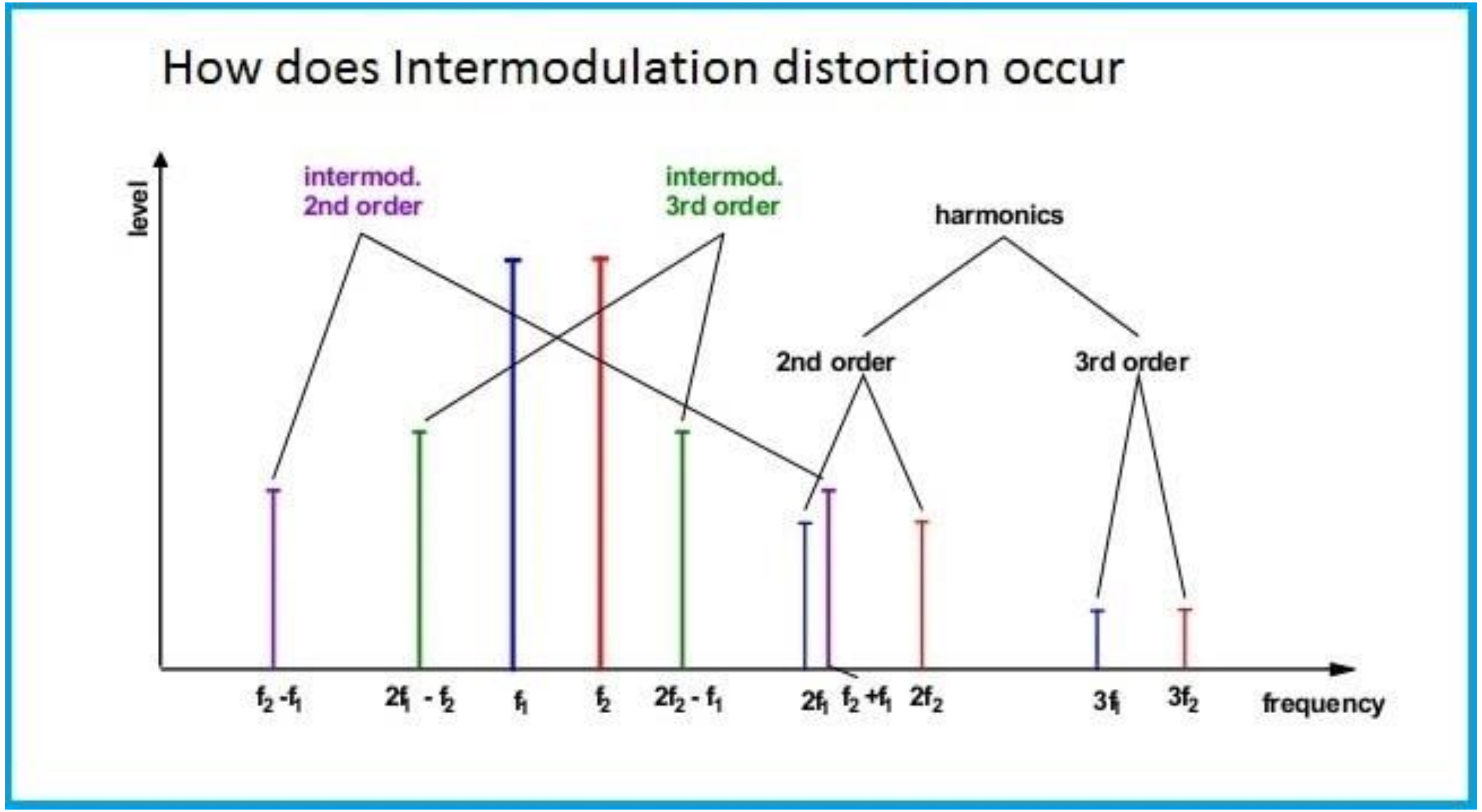
Exciter

Linearity degrades as output increases.



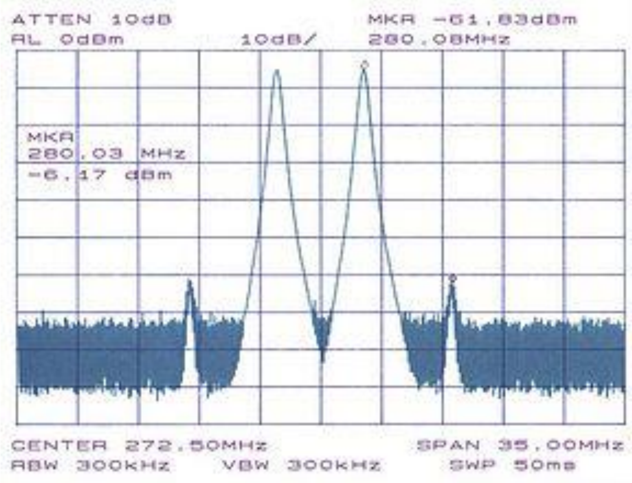
Exciter

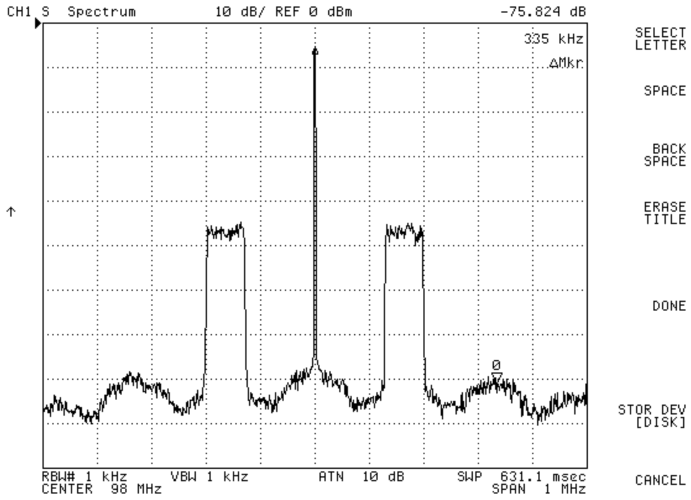
Non-linearity leads to intermodulation distortion which produces multiple spectral products.



Exciter

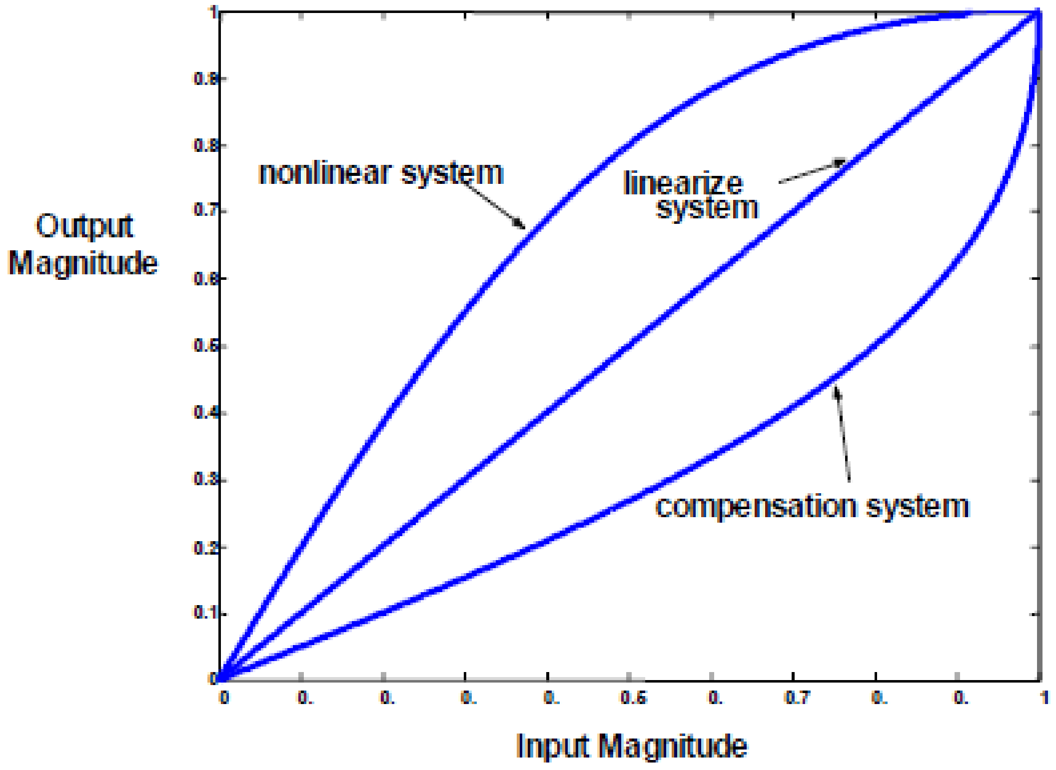
IMD products appear above and below original tones





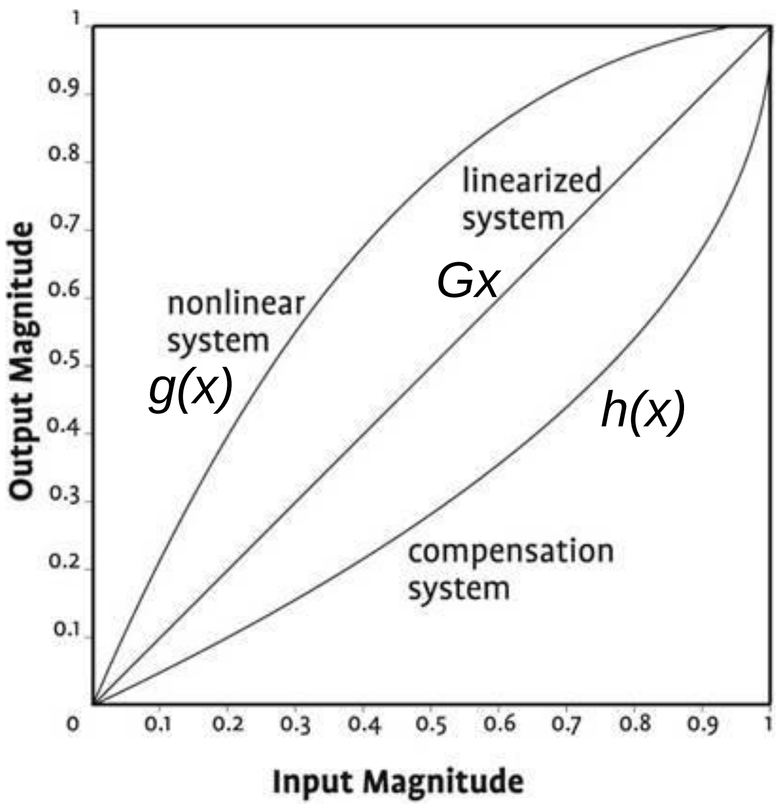
Exciter

In order to create the proper IBOC signal the exciter can now compensate for the distortions in the amplifiers.



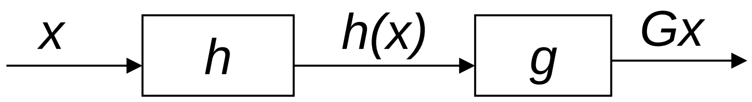
Exciter

Pre-Correction Principle



An amplifier characteristic *g(x)* may be corrected for with a complementary characteristic *h(x)* such that $g(h(x)) = Gx$

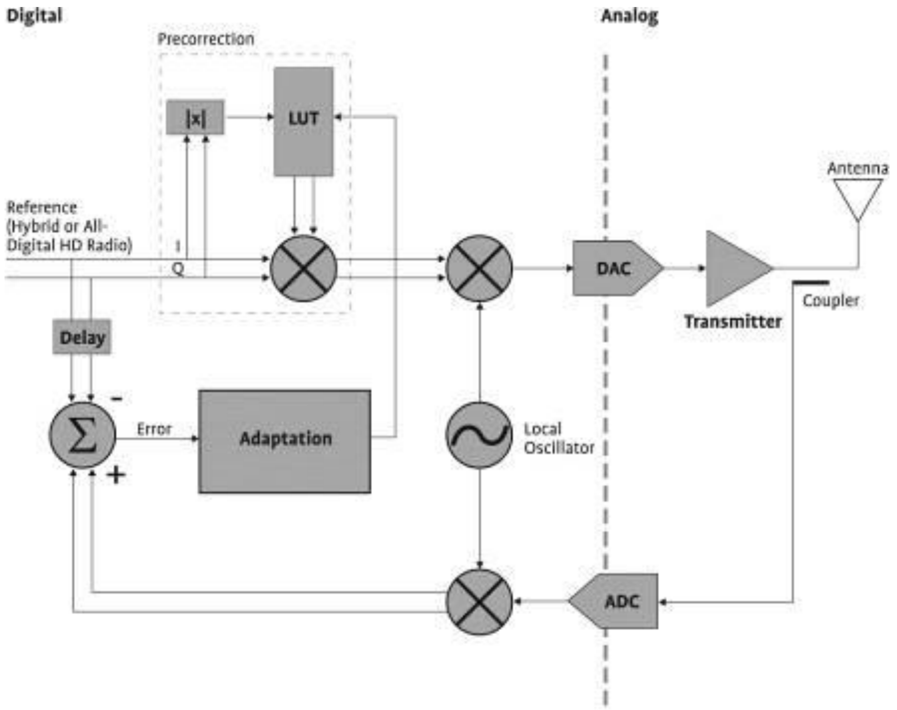
For this to be true, $G\,h(x) = g^{-1}(x)$



Exciter

The M50 Exciter was the first to host digital adaptive Pre-correction

- Corrects primary forms of distortion
- Applies to analog + digital broadcasting
- More Linear – Clean Spectrum
- Adaptive AM-AM correction
- Adaptive AM-PM correction



Exciter

Digital adaptive pre-correction linearizes amplifier and eliminates intermodulation products which exceed out of band emissions

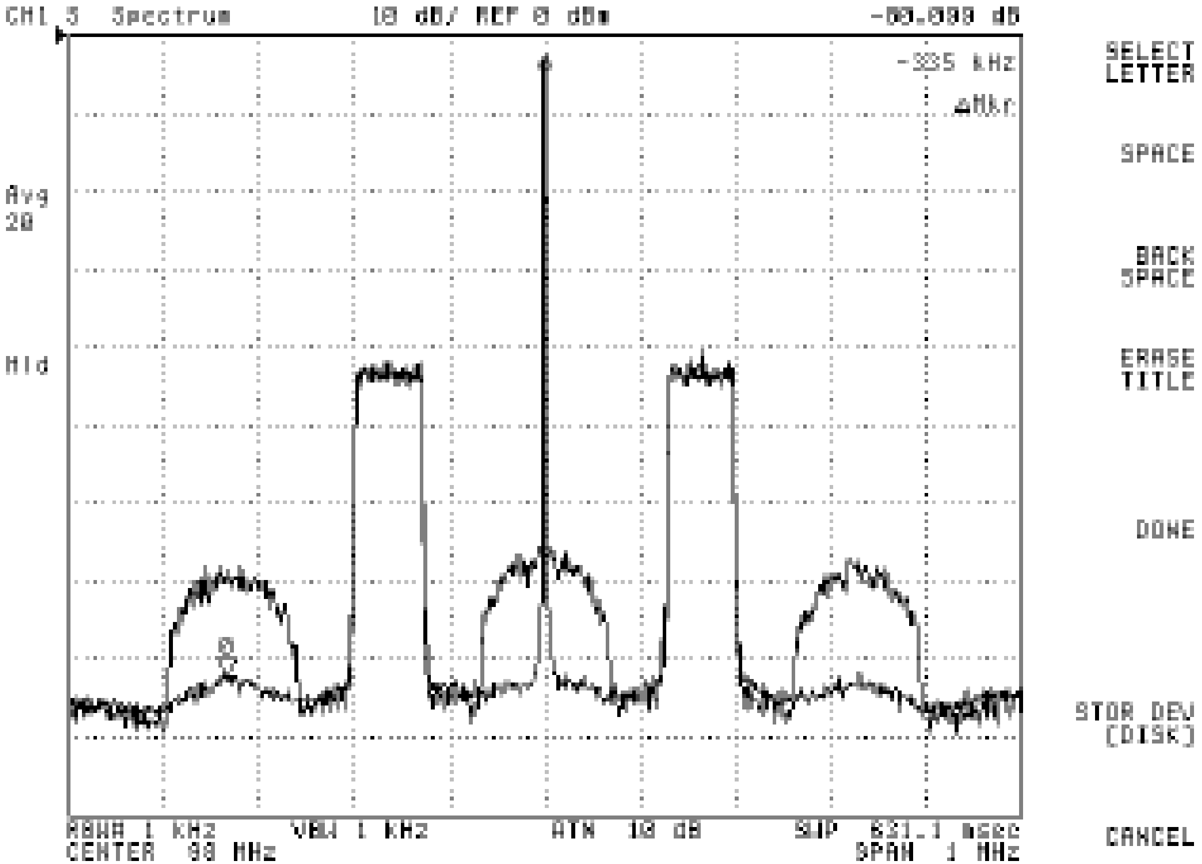


Fig 5 Spectrum of intermod products before and after adaptive pre-correction

Power Supply

Switch-mode power supplies are used in FM transmitter designs.

These power supplies offer:

- Small footprint (W/in^3)
- Single/three phase configurable
- Very good power factor (typ 0.99)
- Excellent efficiency (>96%)

Power Supply

Lessons learned for switching power supply requirements

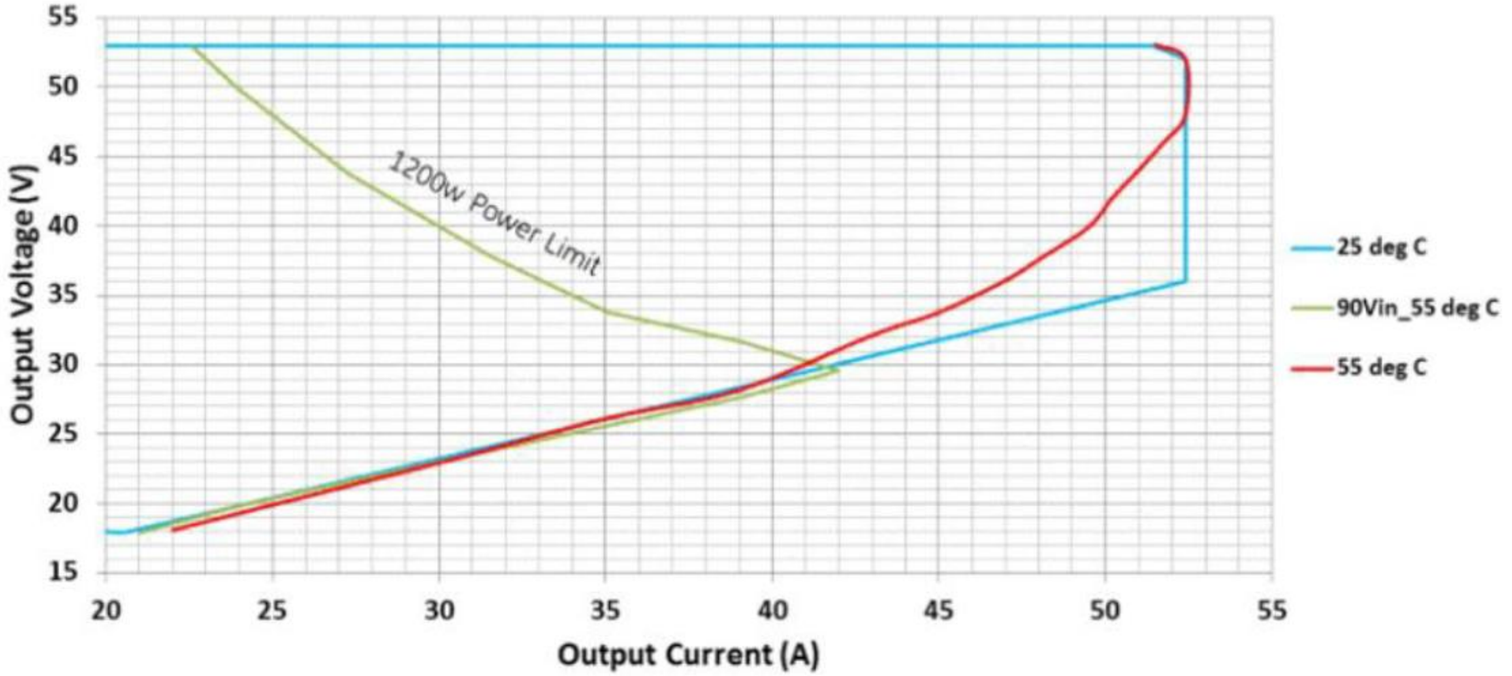
SMPS for FM broadcast--rev3 25may15

Monday, May 11, 2015 6:45 AM

1. Blind mate/hot pluggable
2. Remote adjustable 20-50 VDC
3. Fast AC recovery <5sec
4. Ripple --line related :50 mv rms Fswitching: 50 mv rms
5. Forced air in front, out rear
6. Fan able to tolerate system backpressure--not just free space full spec
7. High reliability failure rate <0.2%/year
8. For 2 x 1kw PA 2000/0.8=2500 watt min Pout for 2 LDMOS PA
9. Adequate margin to run 2500 w 24/7 and meet failure rate criteria

Power Supply

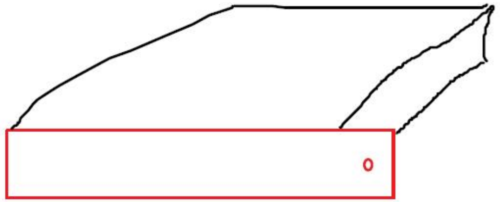
10. Load line --sample below

11. 

12. Able to parallel
13. Low cost 10 cents/watt in 1000 plus pc/yr
14. Fan off when inhibited
15. Conformal coated PWB, No TO220 in PFC or Inverter

Power Supply

23. mechanical retention--simple hole to allow a screw



24. No components (EMI filter) on the line side of internal fuses
25. Must fuse both lines
26. Cy caps should be class Y1 8000 v transient--film preferred
27. Favour a connector that allows wired mains input and PWB pins for all else

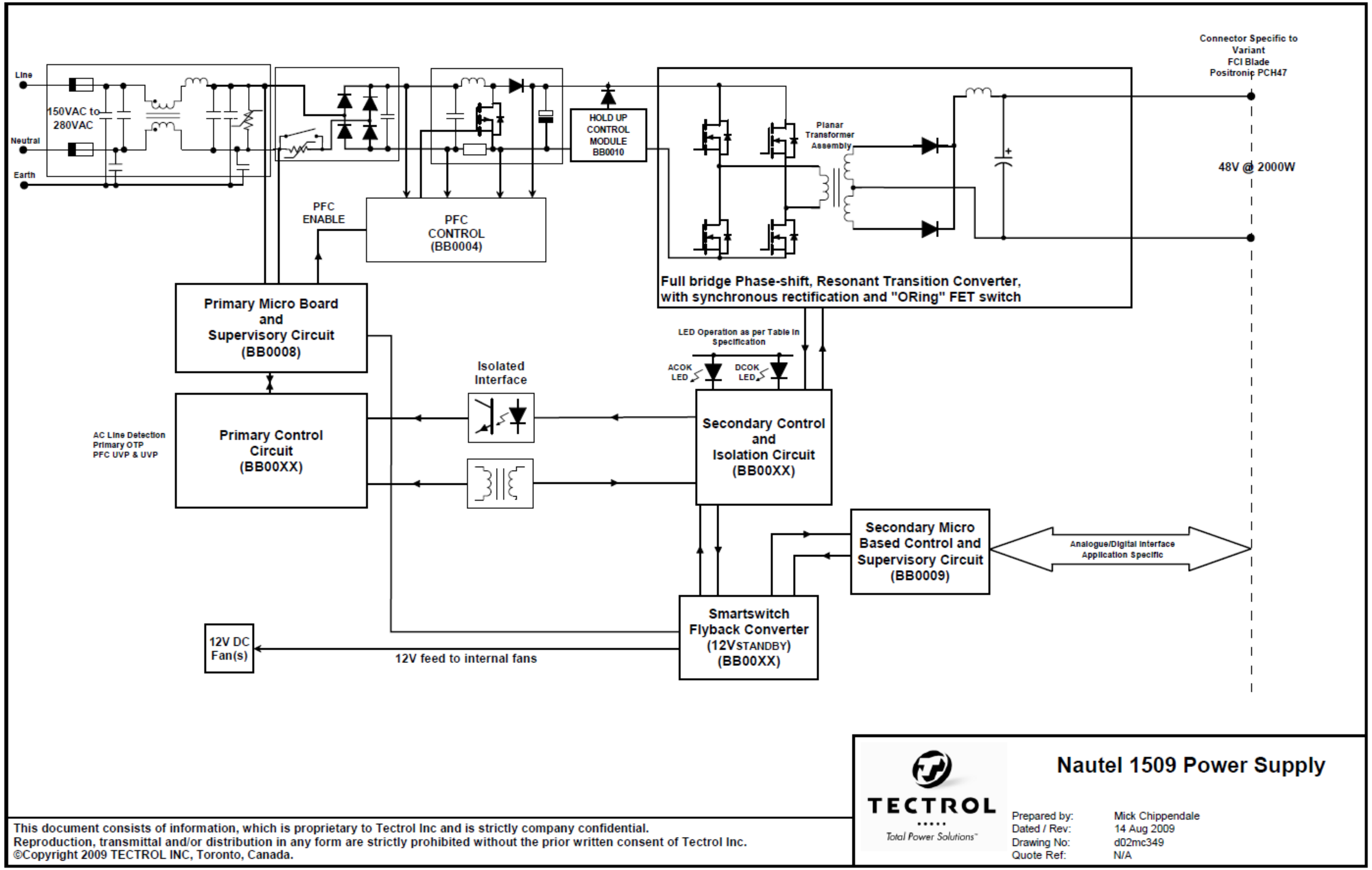
27. The ground return for the hi current must be isolated from the ground return for signals to avoid those smaller tracks becoming alternate paths in parallel with the intended hi current path. A 1 ohm resistor is enough to ensure that the hi current path is preferred.

Power Supply

16. Functional creep 2mm min for 400V
17. Gate drive xfmrs designed for 400 v operation, not for telecom dc/dc
18. Internal temp sensing on critical components to shut down before PS failure in hot ambient -- auto recover
19. Single phase input full Pout 185-305 Vrms, half Pout 90 -185 Vrms
20. Fuse in each input line
21. Transient and sag protection to survive in unreliable power environments (see____)

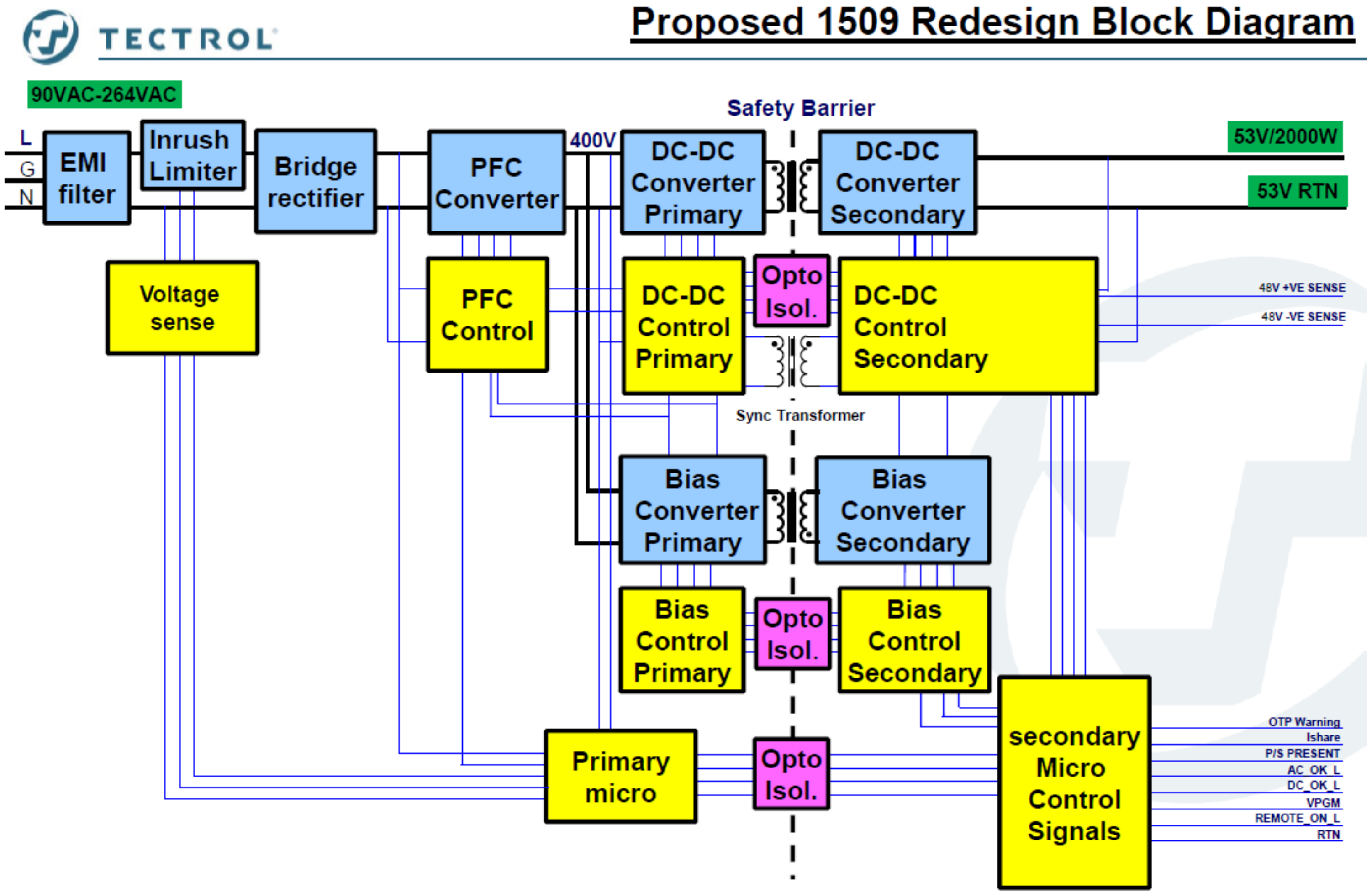
Power Supply

UG69 (NV) power supply block diagram



Power Supply

UG69E (NV)
power supply
block diagram



Power Supply

SMPS AC/DC efficiency continues to improve

PSU Load	Certification						
	Unrated	80 PLUS	80 PLUS BRONZE	80 PLUS SILVER	80 PLUS GOLD	80 PLUS PLATINUM	80 PLUS TITANIUM
20%	Efficiency: 70%	Efficiency: 80%	Efficiency: 82%	Efficiency: 85%	Efficiency: 87%	Efficiency: 90%	Efficiency: 92%
50%	Efficiency: 70%	Efficiency: 80%	Efficiency: 85%	Efficiency: 88%	Efficiency: 90%	Efficiency: 92%	Efficiency: 94%
100%	Efficiency: 70%	Efficiency: 80%	Efficiency: 82%	Efficiency: 85%	Efficiency: 87%	Efficiency: 89%	Efficiency: 90%

Figure 2 - 80 PLUS Certification Tiers

Circuit Board Design

Circuit board creation represents a significant portion of the total transmitter design effort.

Circuit boards typically use copper cladded epoxy resin (FR-4) but sometimes employ high quality materials (ie. Teflon) depending on the application.

FR-4 can operate at approx. 90C before discolouration and delamination.

The copper cladding is quantified in ‘ounces’ with each ounce resulting in 0.0014” thk of copper cladding.

Circuit Board Design

Nautel has strict guidelines for the current that a PWB conductor may carry versus the ounces of copper.

In high voltage applications, there are rules on creepage and clearance distances that must be followed for maximum reliability.

Nautel has an internal 100 point checklist that every PWB must pass before being manufactured.

Cooling

Transmitters employs multiple parallel DC cooling fans which provide:

- redundancy
- high efficiency
- not sync’d to AC line frequency

Protection

Transmitter's control function provides protection such as:

- SWR protection techniques (cutback, foldback, shutback)
- Thermal protection – fan tach, heatsink monitor
- Over current protection
- Over modulation protection

Thank You