# X2Y®


## Technology In Balance

# Common Mode Filters

X2Y® Capacitors

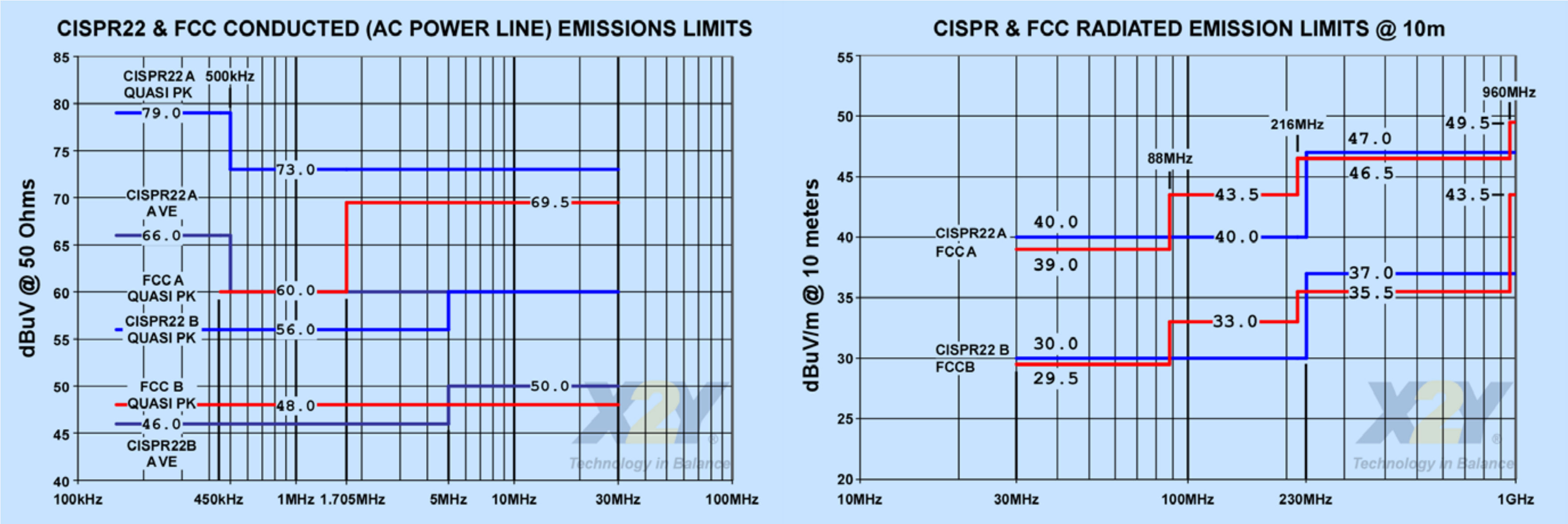
vs.

Common Mode Filters

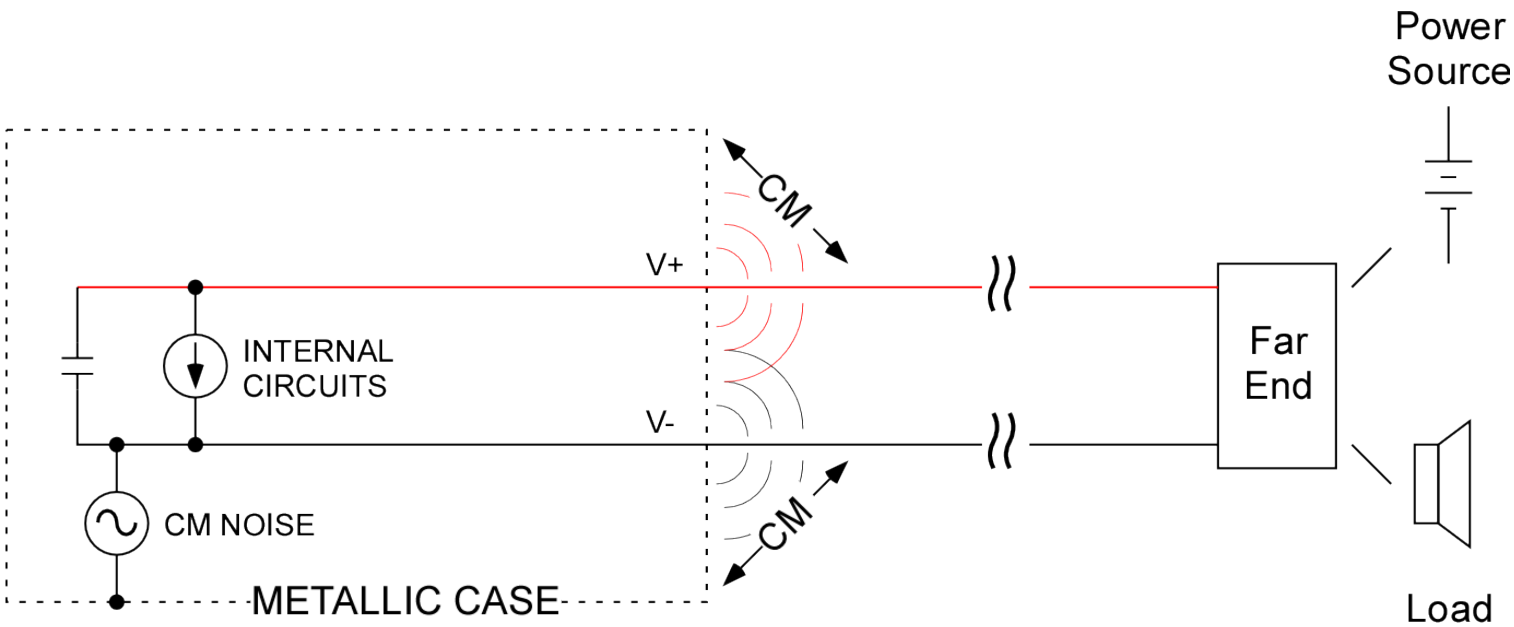
# Contents

# Common Mode and EMI

- Most EMI compliance problems are common mode emissions.
- Only 10’s of uAs in external cables are enough to violate EMC standards.

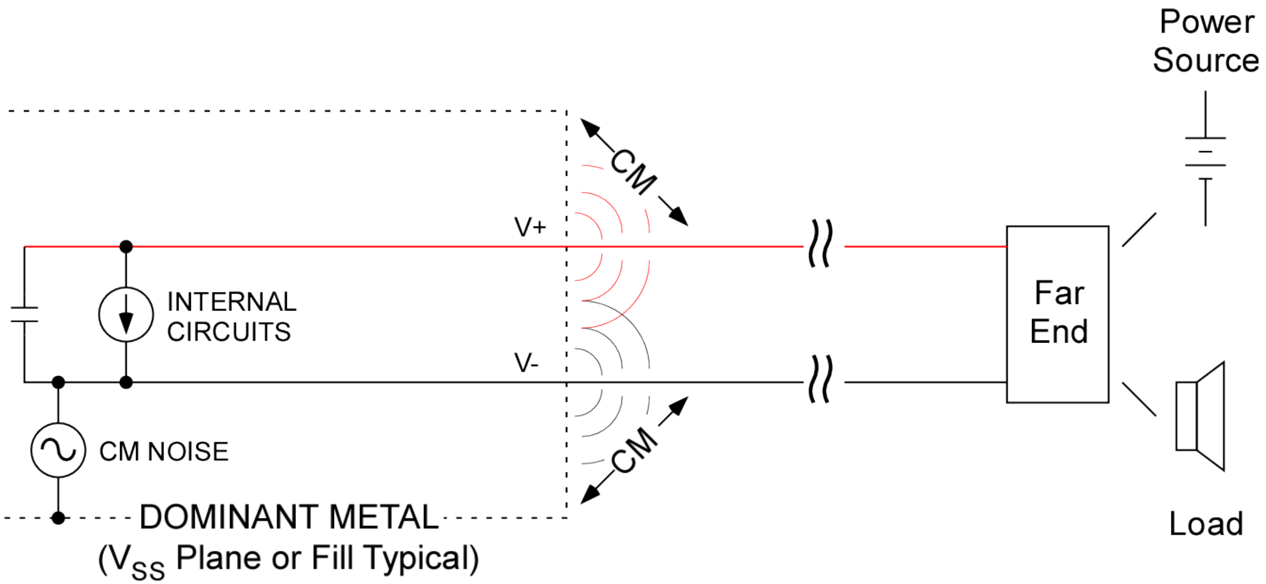


# Common Mode Radiated Noise Model



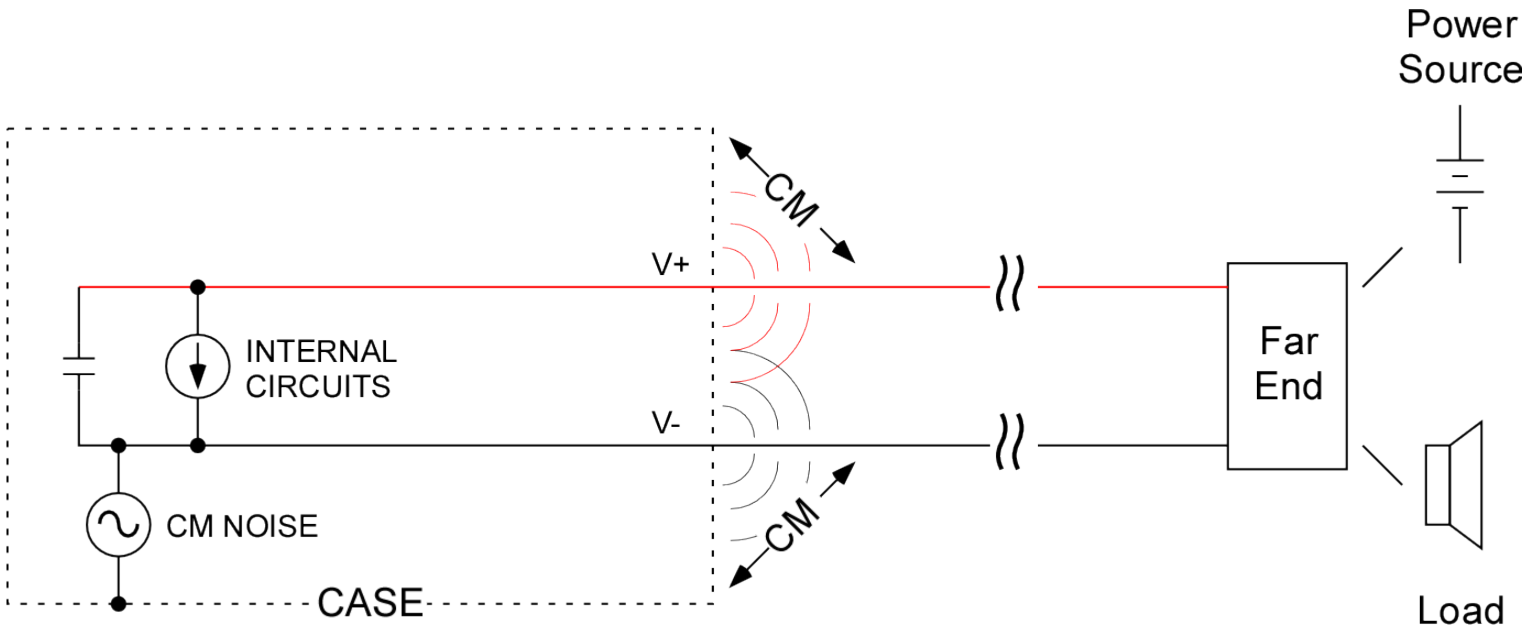

- E field developed between any lead exiting a shielded enclosure and the enclosure outer skin radiates.
- Complementary H field couples to victim antennae.
- Ability to radiate depends on:
  - Power in the noise source
  - Coupling efficiency between the effective antenna structure and the surrounding space
    - Leads and case form the antenna

# Common Mode Radiated Noise Model




- Device w/o metallic case: "CM" develops between dominant external metal, such as Vss solid polygon, or hatch.

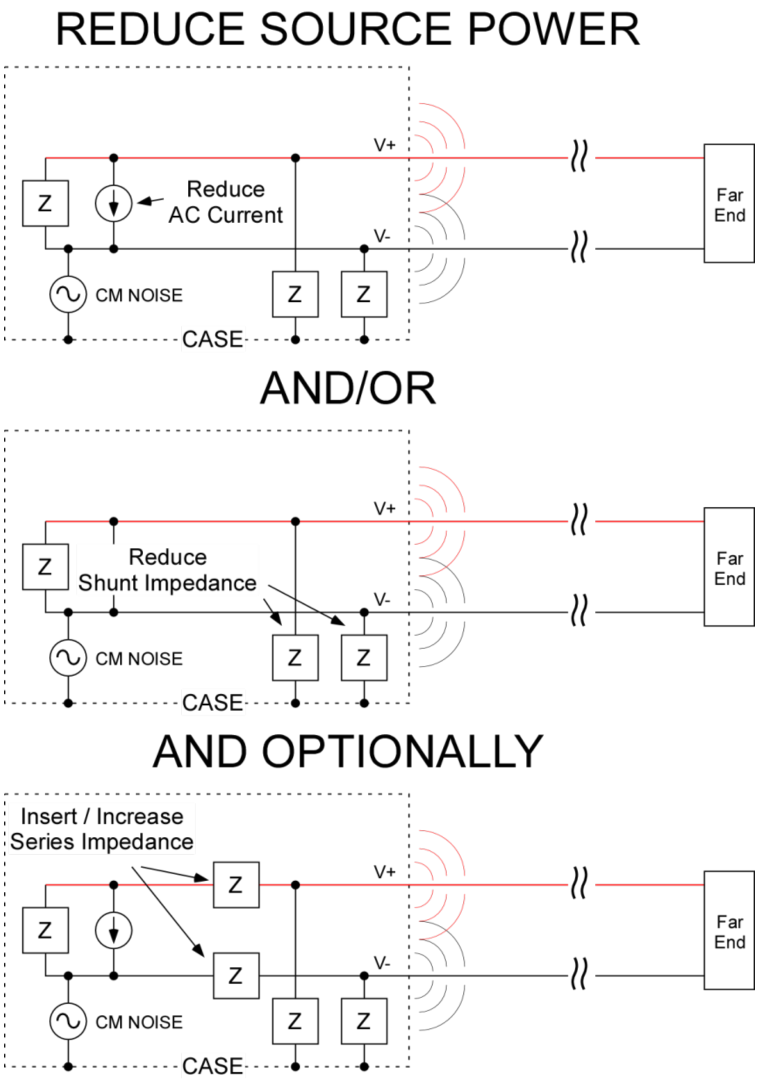
# Common Mode Radiated Noise Model




- Reduce radiation by:
  - Reducing potential between the case and leads, AND/OR
  - Reducing coupling efficiency to surrounding space
    - Reduce antenna gain.
    - Mismatch source impedance to the antenna impedance.

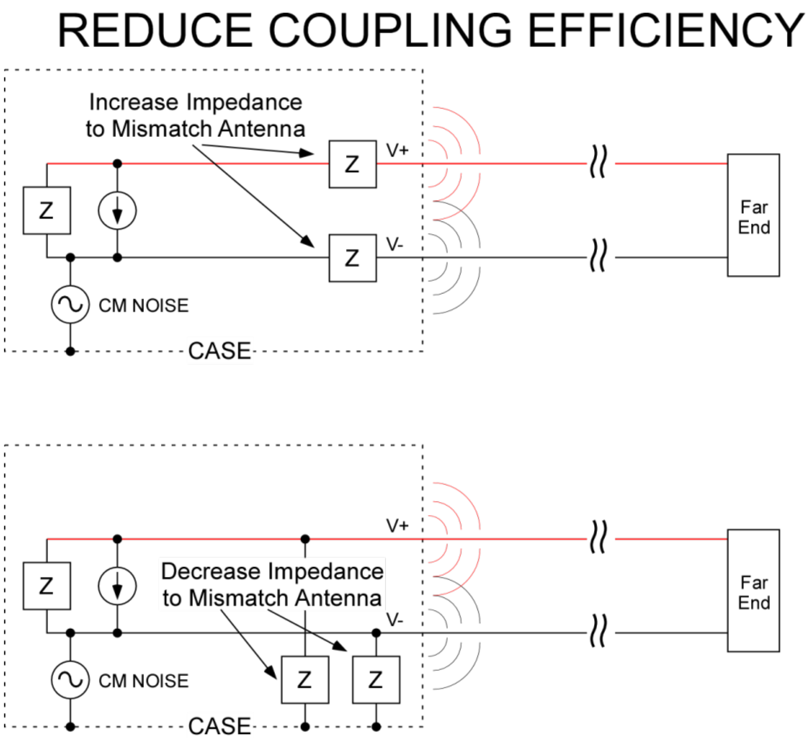
# Reduce CM Source Power

- Reduce HF current in product
  - Rarely an option
- Decrease shunt impedance to case
  - Optionally insert additional series impedance between source and shunt
  - Effectiveness requires low impedance compared to the source and antenna.



# Reduce Coupling

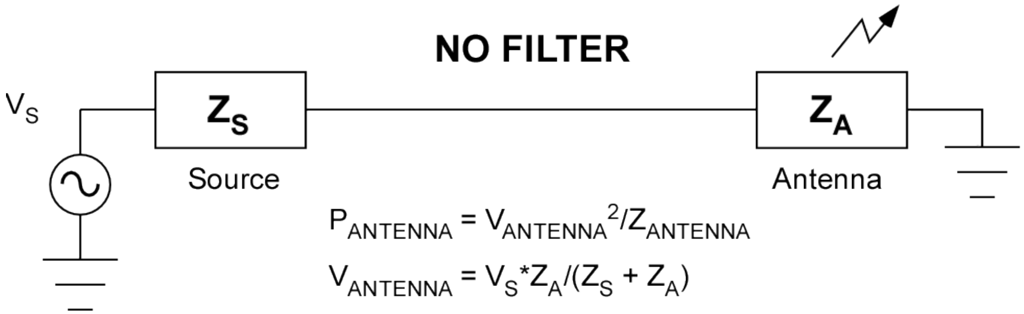
- Reduce antenna efficiency
  - Cable length
  - Cable routing / shielding
- Mismatch antenna impedance
  - Increase driving impedance >> 377 Ohms*
    - Inserted Z effective when >> $Z_{SOURCE} + Z_{ANTENNA}$
  - Decrease driving impedance << 377 Ohms*
    - Inserted Z effective when << $Z_{ANTENNA}$




*Antenna impedance may be anywhere from 10's to 100's of Ohms
Typically 100 – 180 Ohms

# EMI Filter Attenuation

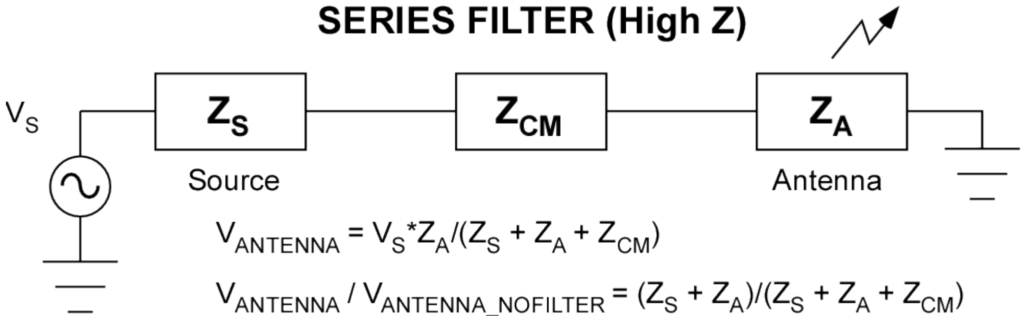
**NO FILTER**




$P_{ANTENNA} = V_{ANTENNA}^2/Z_{ANTENNA}$

$V_{ANTENNA} = V_S * Z_A/(Z_S + Z_A)$

**SERIES FILTER (High Z)**



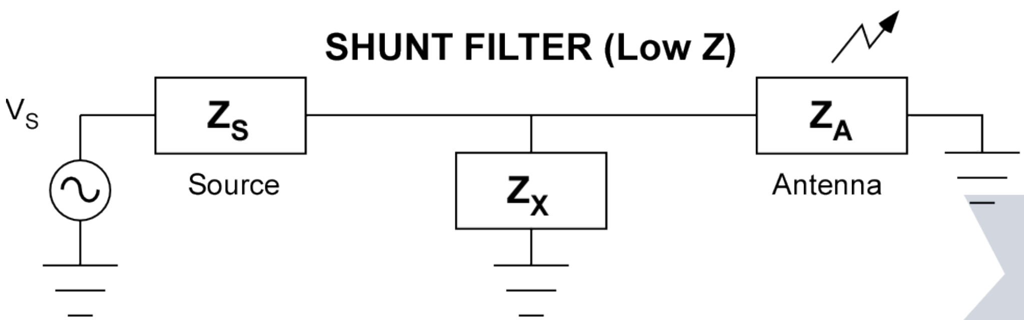

$V_{ANTENNA} = V_S * Z_A/(Z_S + Z_A + Z_{CM})$

$V_{ANTENNA} / V_{ANTENNA\_NOFILTER} = (Z_S + Z_A)/(Z_S + Z_A + Z_{CM})$

**EFFECTIVENESS CRITERIA:**

$Z_{CM} >> (Z_S + Z_A)$

**SHUNT FILTER (Low Z)**



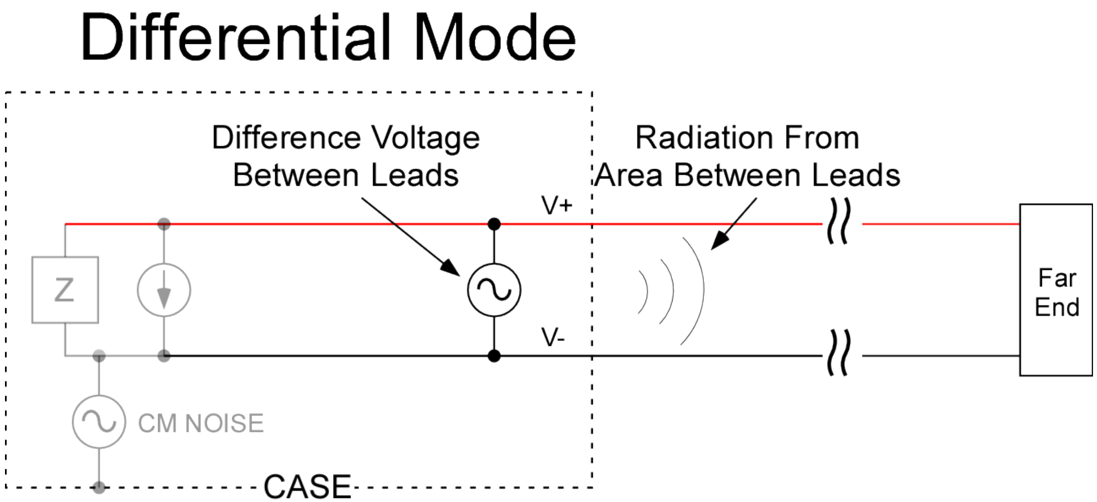

**EFFECTIVENESS CRITERIA:**

$Z_X << Z_S||Z_A$

$V_{ANTENNA} = V_S*(Z_A||Z_X)/(Z_S + Z_A||Z_X)$

$V_{ANTENNA} / V_{ANTENNA\_NOFILTER} = Z_X/(Z_X+(Z_S||Z_A))$

# Differential Mode Radiated Noise Model



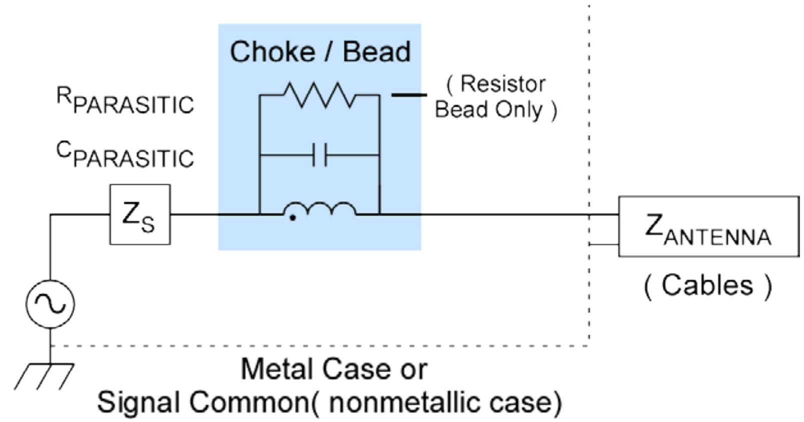

- Voltage(s) between multiple leads that form an antenna in the area between.

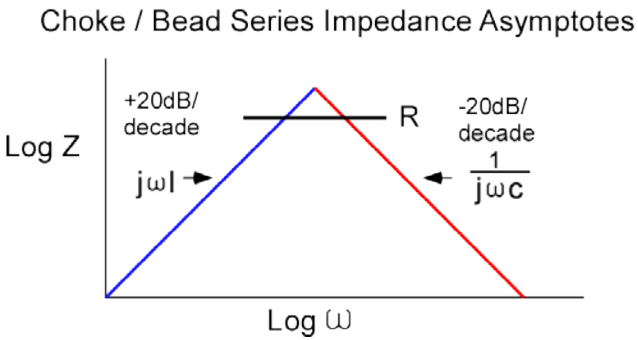
# Mode Conversion

- Occurs when individual filters are not matched.
- Differential signal energy converts into common-mode energy.
- Common-mode energy converts into differential energy.
- Avoid by matching filters throughout stop-band.
- Not an emissions concern where signals do not exist in the noise stop band.
- Mode conversion is a susceptibility concern at all frequencies.

# Single Chokes / Beads as EMI Filters

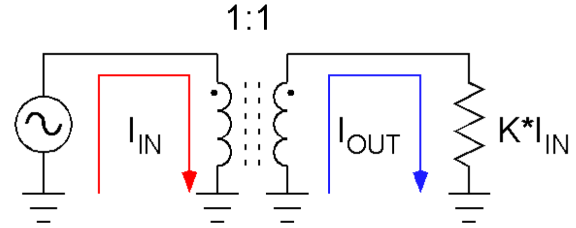
- Chokes attenuate noise emissions when they substantially increase the total noise source impedance relative to the antenna impedance.
  - Insertion loss in dB is:
  - $20LOG((Z_S + Z_A)/(Z_S + Z_A + Z_{CHOKE}))$
- Bead impedance is limited by effective parallel resistance.
  - 600 Ohm bead max insertion loss:
    - -17dB: 50Ω source / 50Ω antenna
    - -12dB: 50Ω source / 150Ω antenna
- Chokes and beads limited at high frequency by parasitic mounted capacitance.
  - Device & mounting structure capacitance in parallel
  - PCB layout & adjacent components can defeat insertion loss



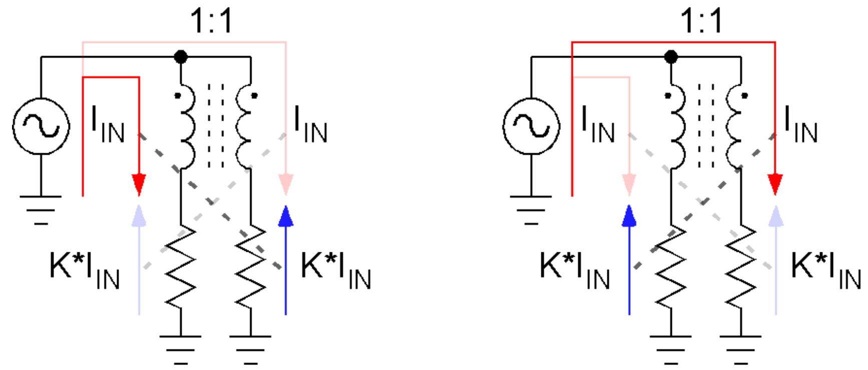



# CM Choke Mechanics

- A CM choke couples chokes on a common core
  - Usually two windings / core.
  - Coupling improves CM rejection on each lead in the stop band,
  - CM chokes can pass differential signals in the stop band.
- A CM choke is a 1:1 transformer where the primary and secondary are both driven.
  - Both windings act as both primary and secondary.
  - Current through one winding induces an opposing current in the **other** winding.
  - For K close to 1.0, total effective CM impedance is:
    - $Z \approx 2\pi F * L_{MAG}$
    - 2X what two independent chokes with the same $L_{MAG}$ would yield.




1:1 Transformer, 0.95 <= K <= 0.99



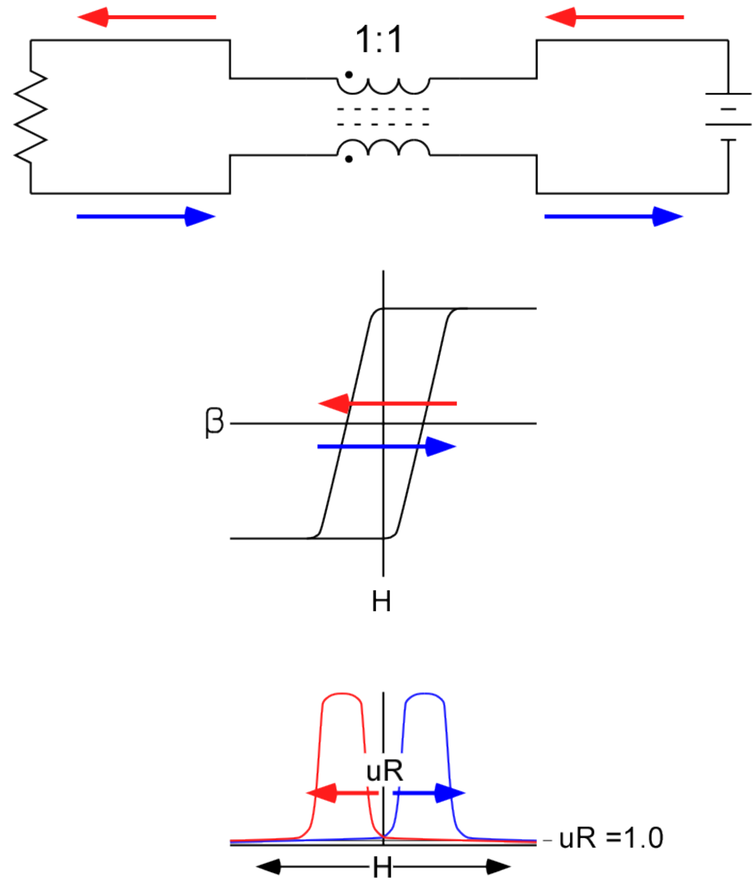

$I_{OUT} = 2*(V_{IN}/Z*(1+K))$

CM CHOKE, 0.98 <= K <= 0.99

# CM Choke Mechanics

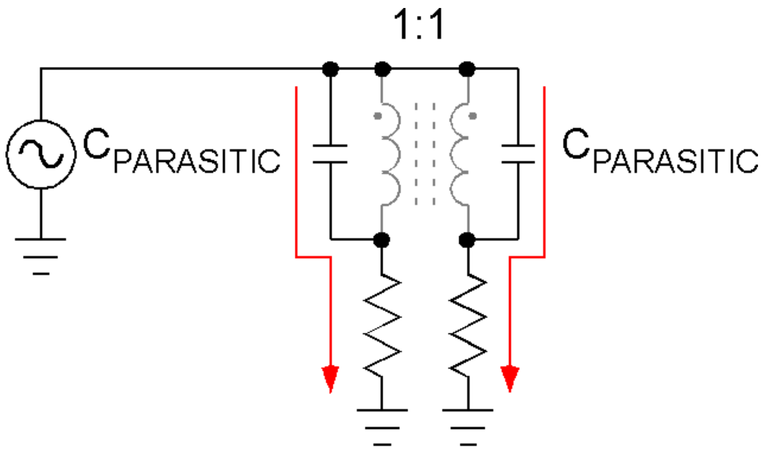
- CM choke winding coupling **DOES NOT** cancel all or even a high percentage of CM noise.
- CM chokes **DO** increase CM inductance **up to 2X** compared to each of two independent chokes of the same open circuit inductance rating.
- CM chokes **DO** cancel most core flux allowing much higher CM currents w/o saturation than two independent chokes of the same material and core size.
  - Allows DC and AC to pass as differential currents w/o killing CM attenuating inductance
  - Important to power filter applications that use chokes
    - DC balance must be maintained in wiring and load.

CM CHOKE DC FLUX CANCELLATION



# CM Choke Mechanics

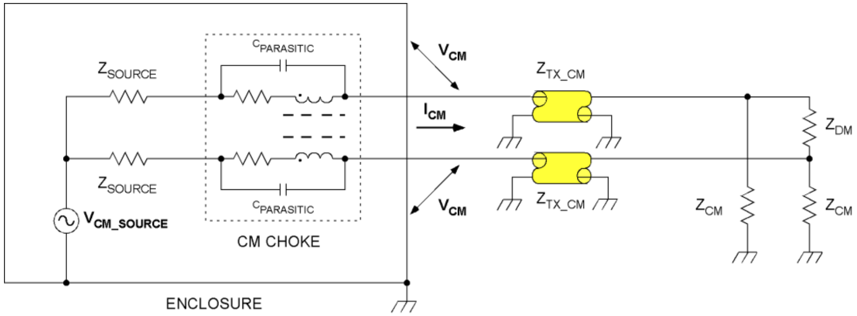
- Just as with individual chokes / beads, parasitic capacitance limits the effective frequency range of CM chokes.
- For a given core material, the higher the inductance used to obtain lower frequency filtering, the greater the number of turns required and consequent parasitic capacitance that defeats high frequency filtering.
- At frequencies > $F_{SRF}$, parasitic capacitance defeats impedance gain from coupled windings.

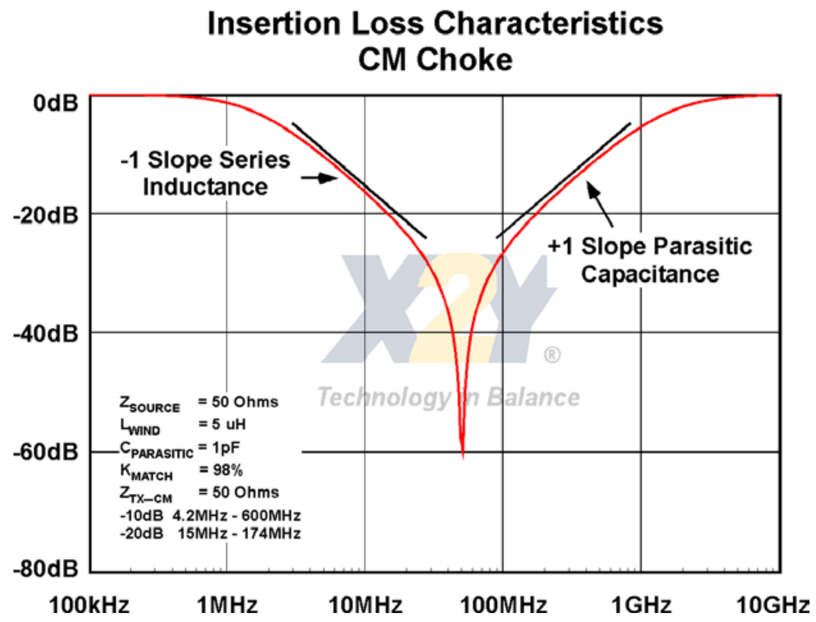



Capacitor current bypasses the transformer coupling. At frequencies > $F_{RES}$ impedance is capacitive and low.

# Choke/Bead/CM Choke Bandstop

- Insertion loss declines past $F_{SRF}$ due to parasitic shunt capacitance.
  - Parasitic capacitance, noise source impedance and lead antenna impedance define high frequency noise attenuation.
  - Parasitic capacitance is combined effects of the CM Choke and the CM Choke PCB mount.
  - Very small capacitances, < 1pF can have very big effects above 100MHz
  - 1pF Limits 1GHz Insertion Loss:
    - -8dB: 50Ω source / 50Ω antenna
    - -5dB: 50Ω source / 150Ω antenna
- $F_{SRF} = 1/(2\pi(\sqrt{(L_{CM} * C_{PAR})}))$

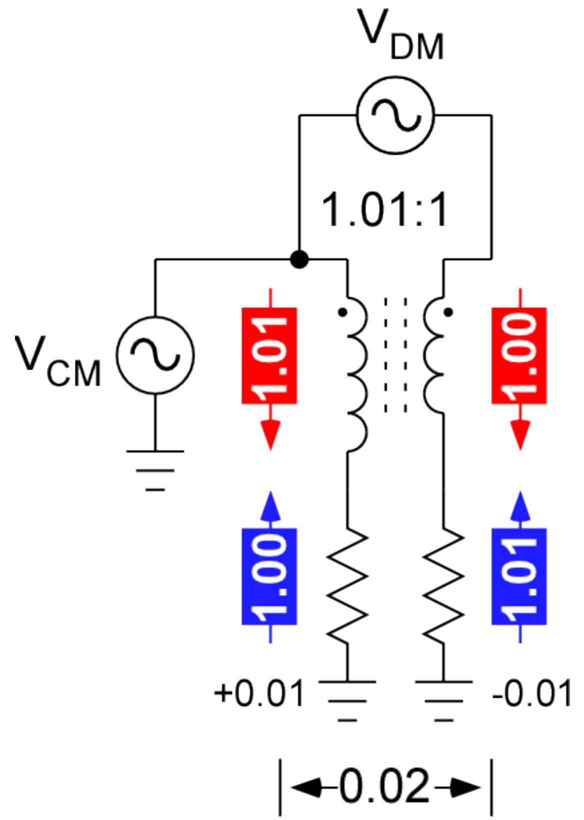


# CM Chokes Winding Mismatch

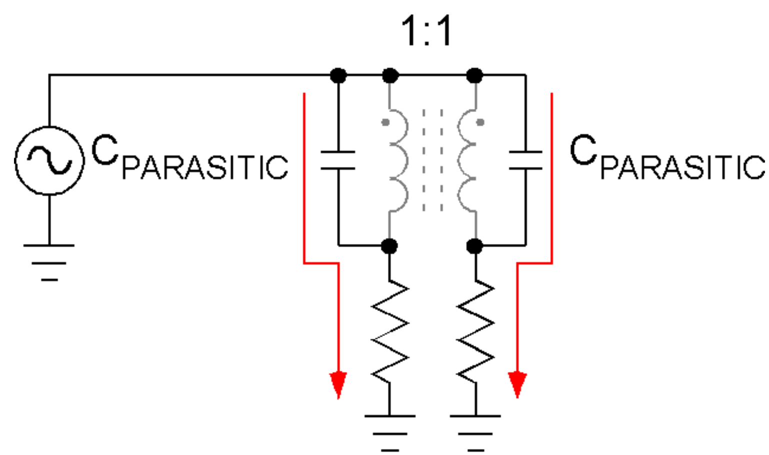
- Mismatch between windings from mechanical manufacturing tolerance causes mode conversion.
  - A percentage of signal energy converts to common mode, and vice-versa.
  - This gives rise to EMC issues as well as immunity issues.
- Mismatch reduces the effective inductance in each leg.
  - $L_{EFF} \approx L_{MAG} * (1+K_{MATCH})$
  - $0.9 < K_{MATCH} < 0.99$

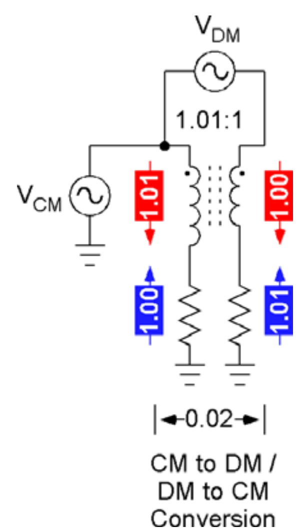


CM to DM / DM to CM Conversion

# CMCs Stop Band Mode Conversion

- Parasitic capacitance and winding mismatch both defeat inductive cancellation in the stop band causing mode conversion.
- Not a major radiation concern where signal energy is negligible in the stop band.
  - Conditions under which a shunt filter is a viable alternative.

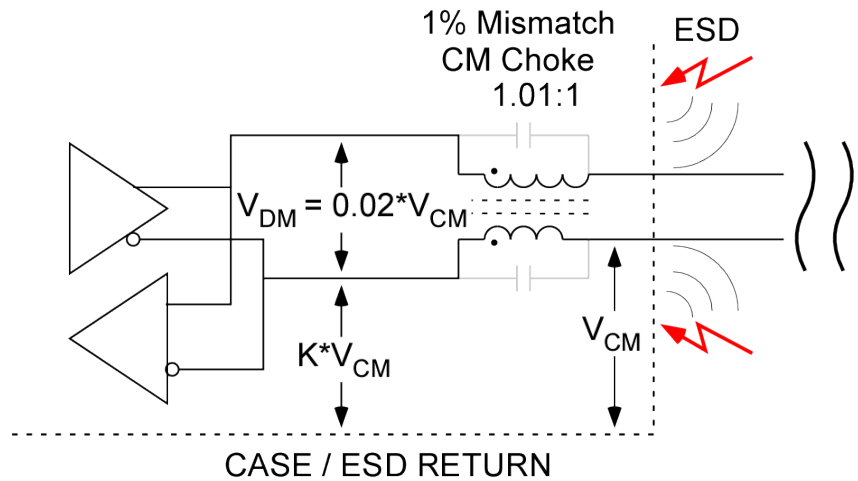


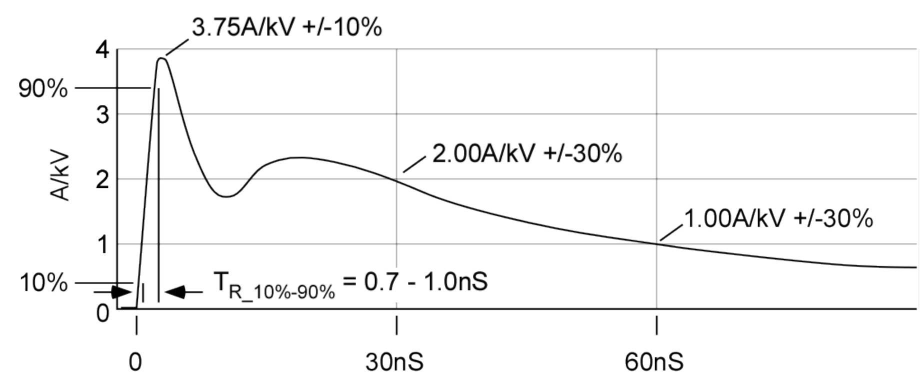



# CMCs Mode Conversion Susceptibility

- ESD discharge onto case induces common mode voltage onto cables.
  - Standard test waveform leading edge knee frequency: 300-500MHz
- Mode conversion increases susceptibility of internal circuits to outside noise:
  - 1% Magnetics mismatch => 2% of CM voltage appears as difference voltage across leads
- Similar mechanics for power leads.

CM CHOKE ESD / EFT SUSCEPTIBILITY DUE TO MODE CONVERSION BELOW $F_{SRF}$

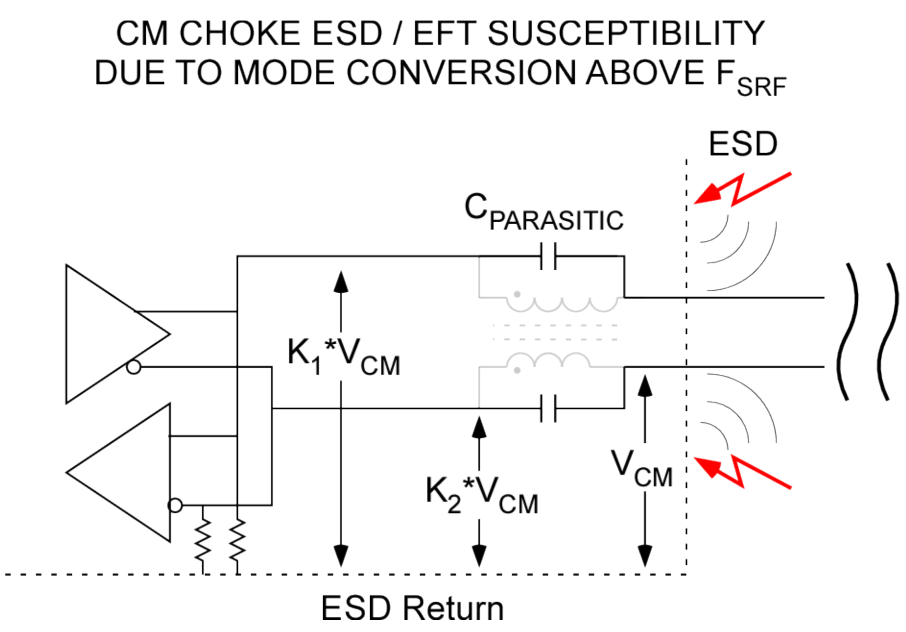



IEC 61000-4-2 ESD DISCHARGE WAVEFORM

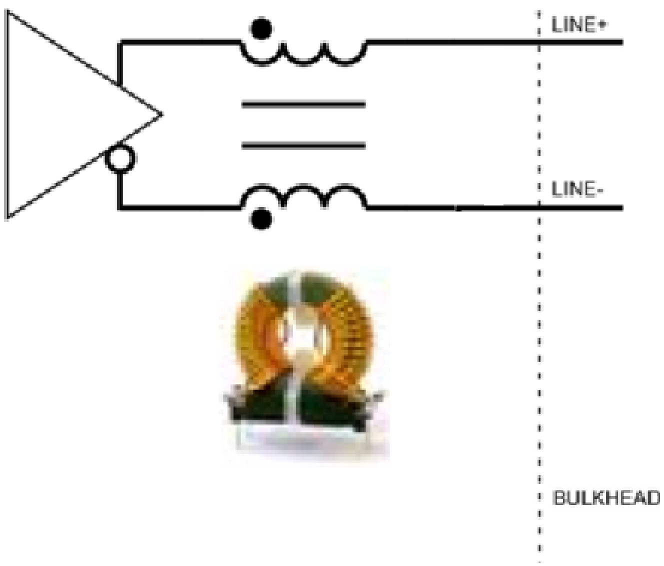
# CMCs Mode Conversion Susceptibility

- At frequencies above filter $F_{SRF}$, voltage passed through each winding depends on:
  - Choke parasitic capacitance,
  - Layout, and
  - IC input matching.
- Add transient voltage suppression devices, TVS, to protect ICs / power system



# CM Chokes as EMI Filters

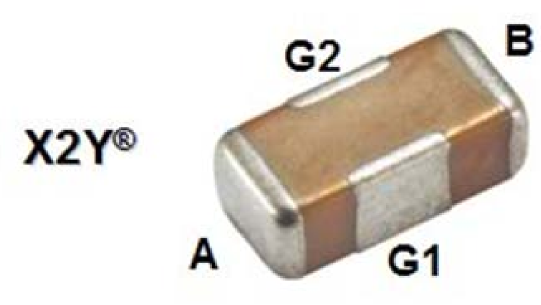
- CM chokes have one really good application:
  - Signals must be passed that operate in the same frequency range as CM noise that must be suppressed.
  - Mode conversion and winding mismatch is a major concern in these applications.
- Otherwise: CM chokes are: large, heavy, expensive, and subject to vibration induced failure.
- Estimating CM performance
  - Example: 4.7mH $L_{CM}$, 3pF $C_{PAR}$:
  - $F_{SRF}$ = 1.3MHz
  - $IL_{dBMAX}$ = 20LOG(100/8.4E6)
  - ≈ -52dB

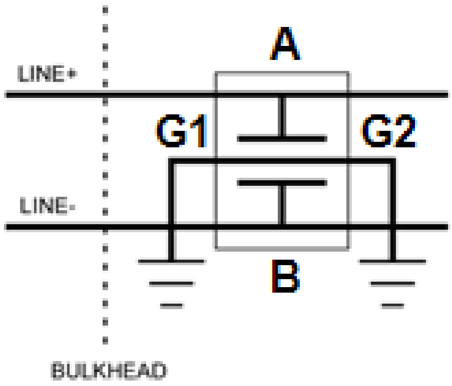


# X2Y® Capacitors, Nearly Ideal Shunts

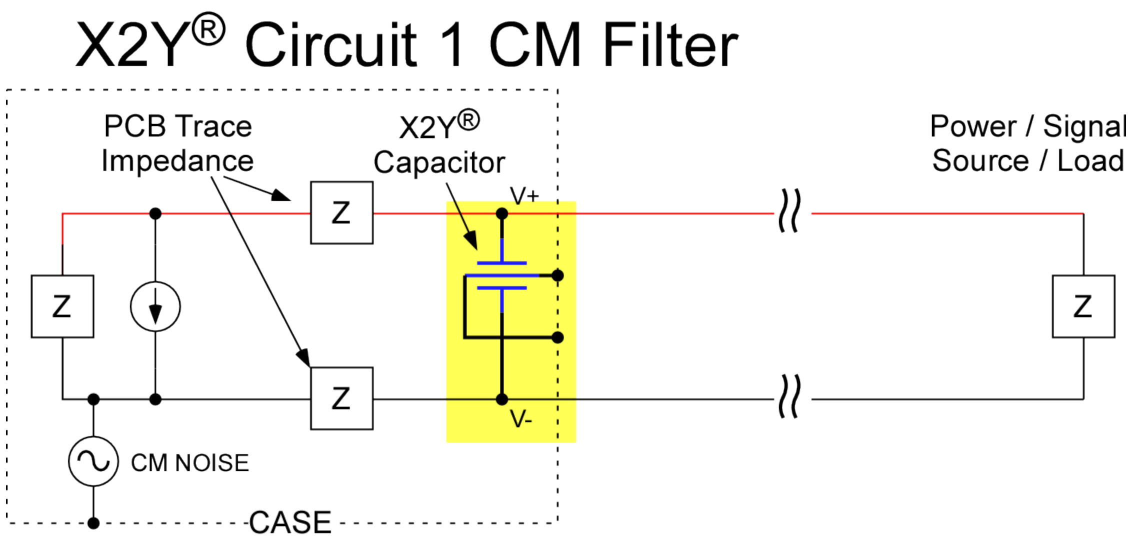
- Two closely matched capacitors in one package.
  - Effects of temperature and voltage variation eliminated
  - Effect of ageing equal on both lines
- Very low inductance between terminals.



# X2Y® Capacitors, Nearly Ideal Shunts

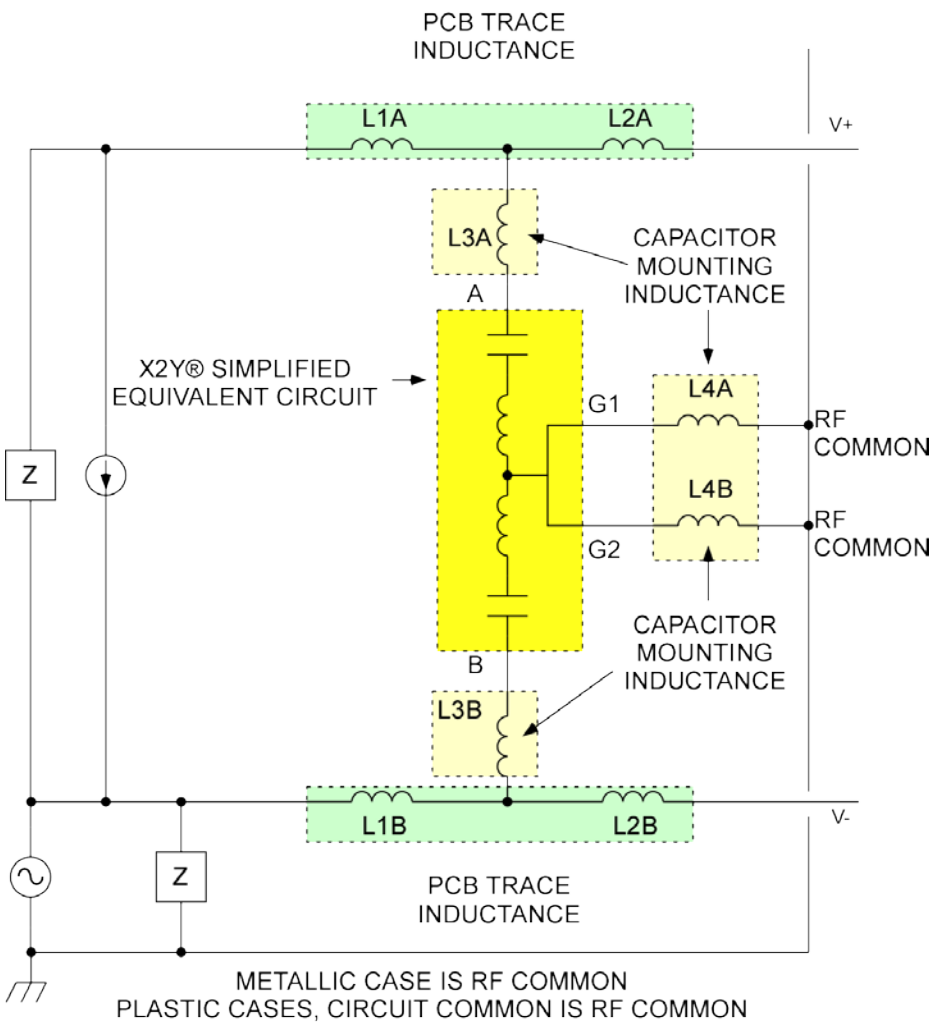
- When properly applied, X2Y® capacitors filter CM noise by ***both*** attenuating source energy, and mismatching antenna impedance.
- The key is very low, and matched inductance.
- Proper application must mind inductance in the common path: G1/G2 terminals.



# X2Y® Capacitors, Nearly Ideal Shunts

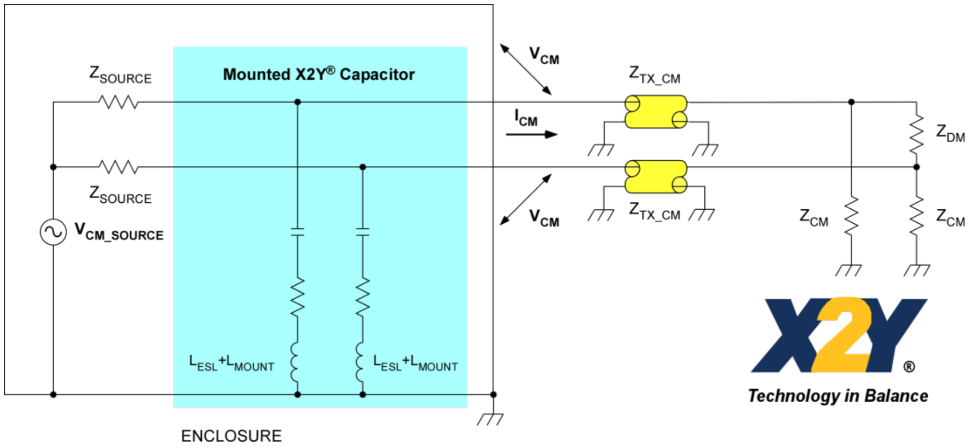
- X2Y® capacitor shunts between A, B, and G1/G2 attachments.
  - Component inductance is very low:
    - ≈110pH from each A or B to G1/G2.
- Low impedance shunt serves two purposes:
  - Divides noise voltage
  - Mismatches external antenna impedance
    - Reflects inside noise back inside
    - Reflects external noise: EFT/ESD back towards outside.
- Performance is typically limited by external capacitor mounting inductance relative to protected traces and RF common:
  - L3A/L3B, L4A, L4B
  - Minimize w/ best practices
    - See slides 52-54 for technique
  - RF common is the case for metallic enclosures.
  - RF common is circuit common for non-metallic enclosures

X2Y® Circuit 1 CM Filter

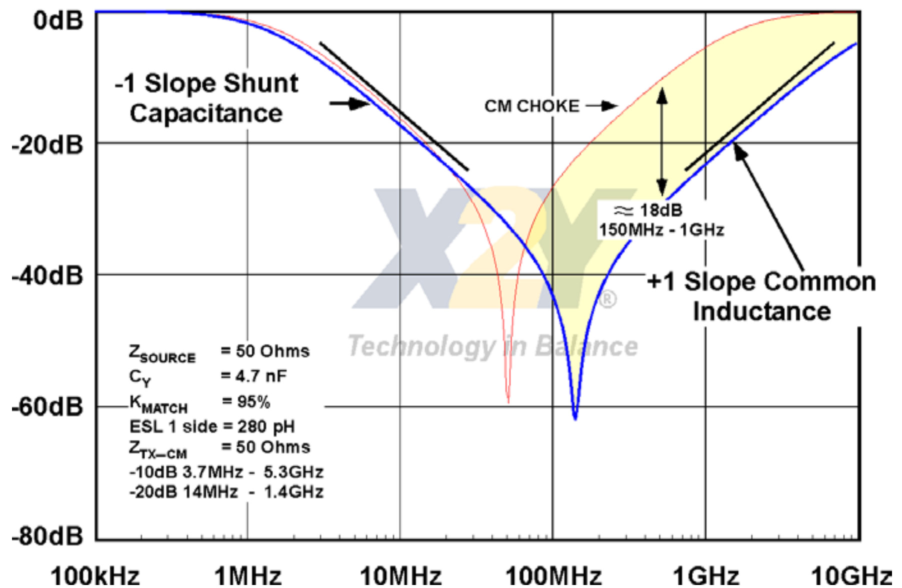


# X2Y® Bandstop

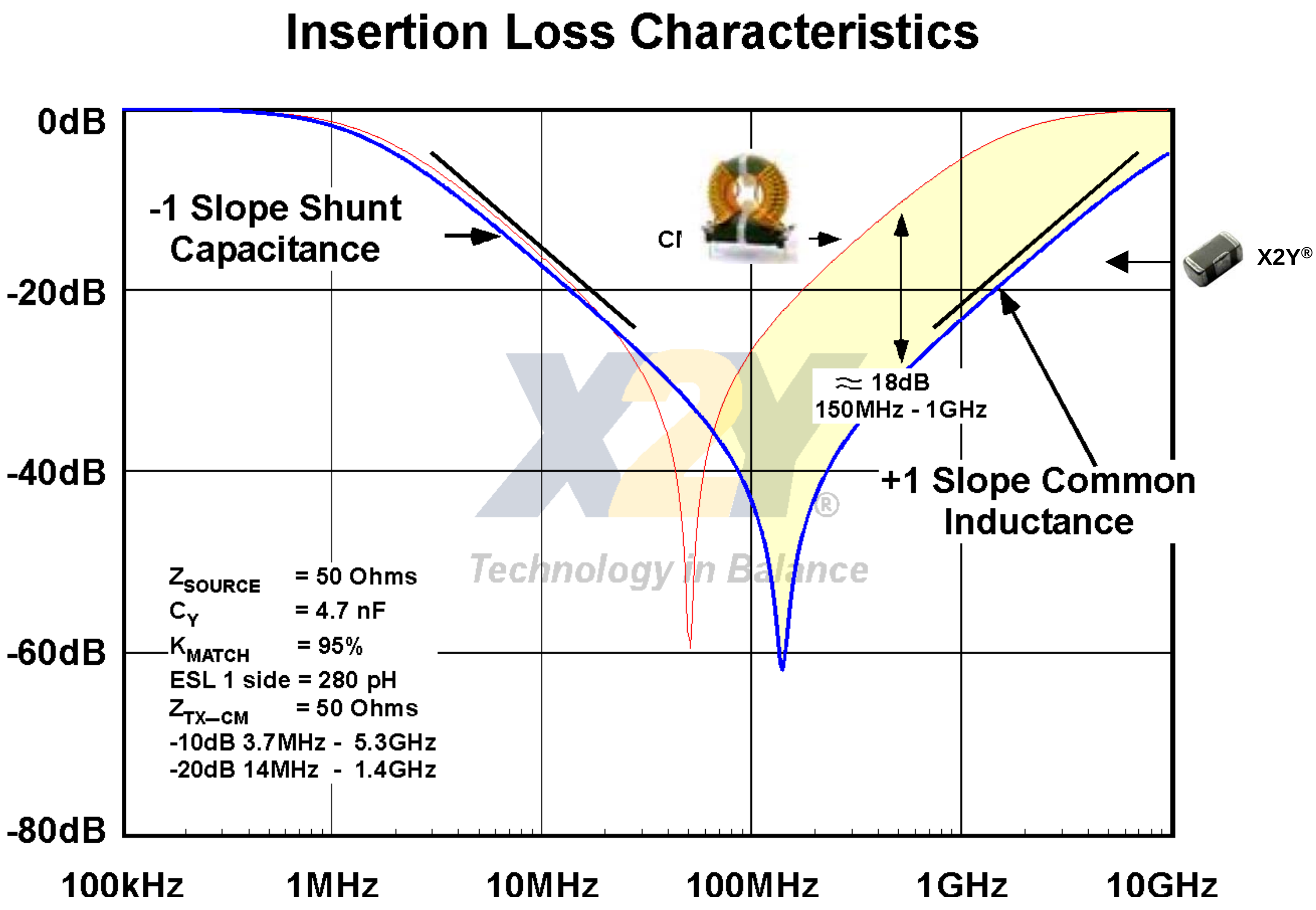
- Insertion loss builds up to $F_{SRF}$ due to parallel capacitance.
- Insertion loss declines past $F_{SRF}$ due to parasitic common inductance.
- Y capacitor mismatch reduces insertion loss below $F_{SRF}$.
  - Increases low frequency cut-off by ≈ $2/(1 + K_{MATCH})$
  - $0.9 < K_{MATCH} < 0.99$
  - Generally no concern




Insertion Loss Characteristics
X2Y® Capacitor



# X2Y® vs. CM Choke Bandstop

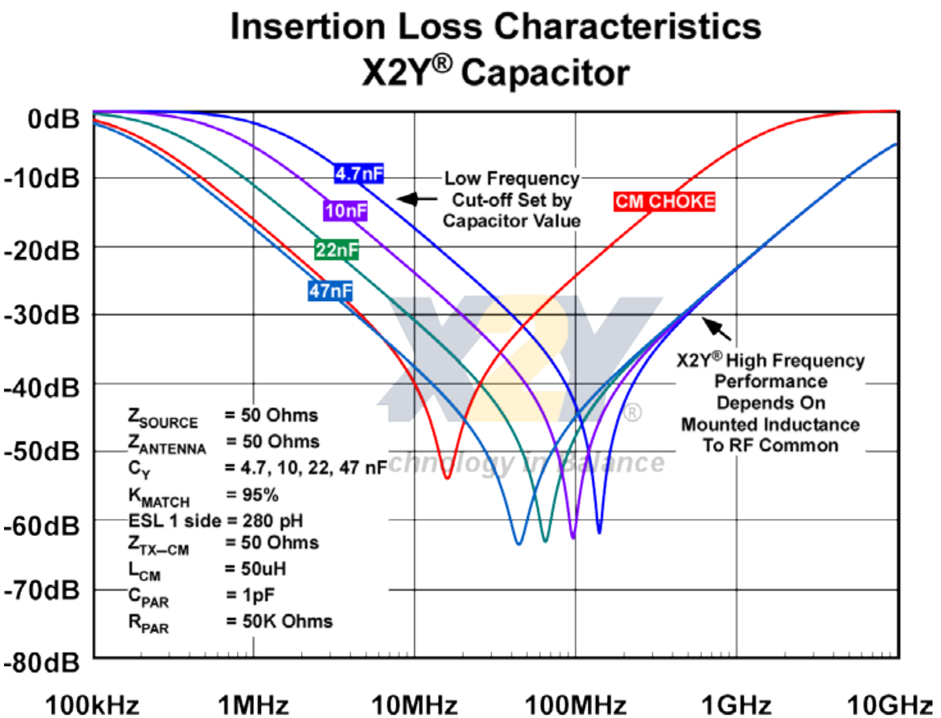


# X2Y® Bandstop

- **Insertion Loss:**

  $20LOG(Z_{X2Y}/(Z_{X2Y}+(Z_{SOURCE}||Z_{ANTENNA}))$

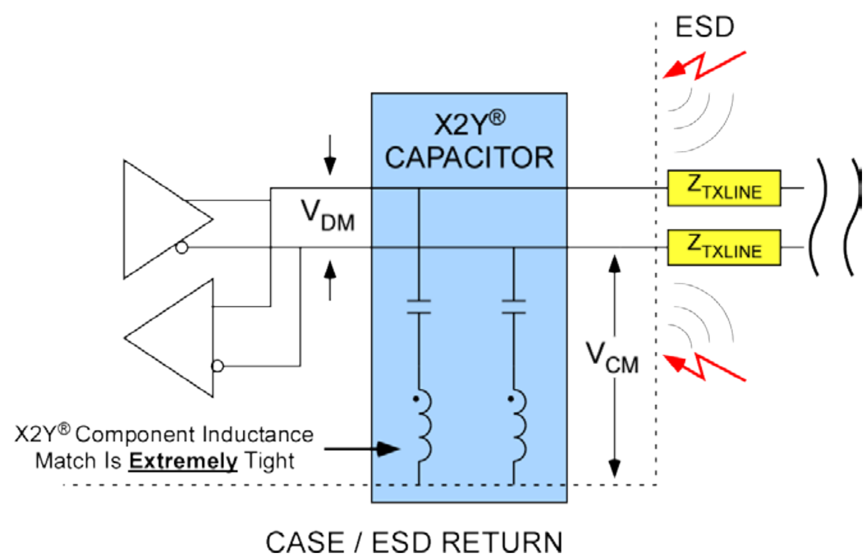
- **Low frequency performance** determined by X2Y® capacitance.
  - Increase capacitance as required to set filter lower cut-off frequency.
- **High frequency attenuation** determined by:
  - Mounted capacitor common inductance.
  - Essentially constant across X2Y® values.
- **Insertion Loss @1GHz**
  - Using 4mil top dielectric PCB
  - -24dB: 50Ω $Z_{SOURCE}$ / 50Ω $Z_{ANTENNA}$
  - -27dB: 50Ω $Z_{SOURCE}$ / 150Ω $Z_{ANTENNA}$
- Unique X2Y® advantage:
  - Larger capacitors do not hurt HF performance.



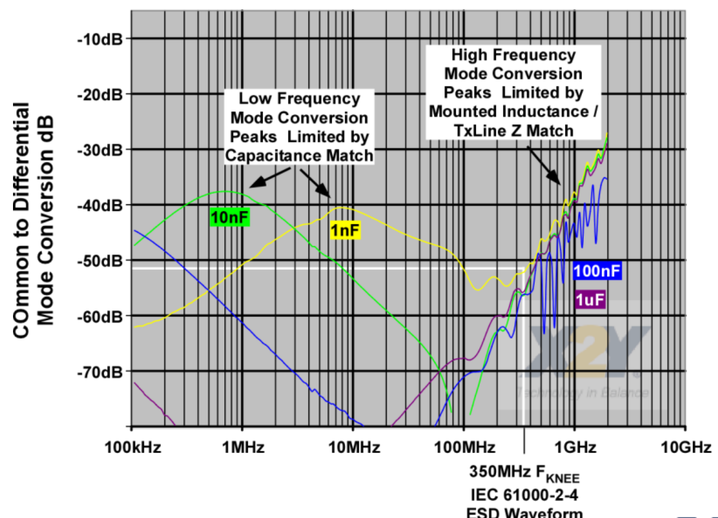
# X2Y® and ESD/EFT Susceptibility

- **X2Y®** is a shunt solution with very low and **matched** parasitic inductance.
  - Common mode attenuation is high over a wide frequency range.
  - Mode conversion has two contributors:
    - @Low frequencies: capacitor value matching.
    - @High frequencies: inductance matching.
- Mode conversion for 1nF and larger parts, @ 350MHz is better than -50dB

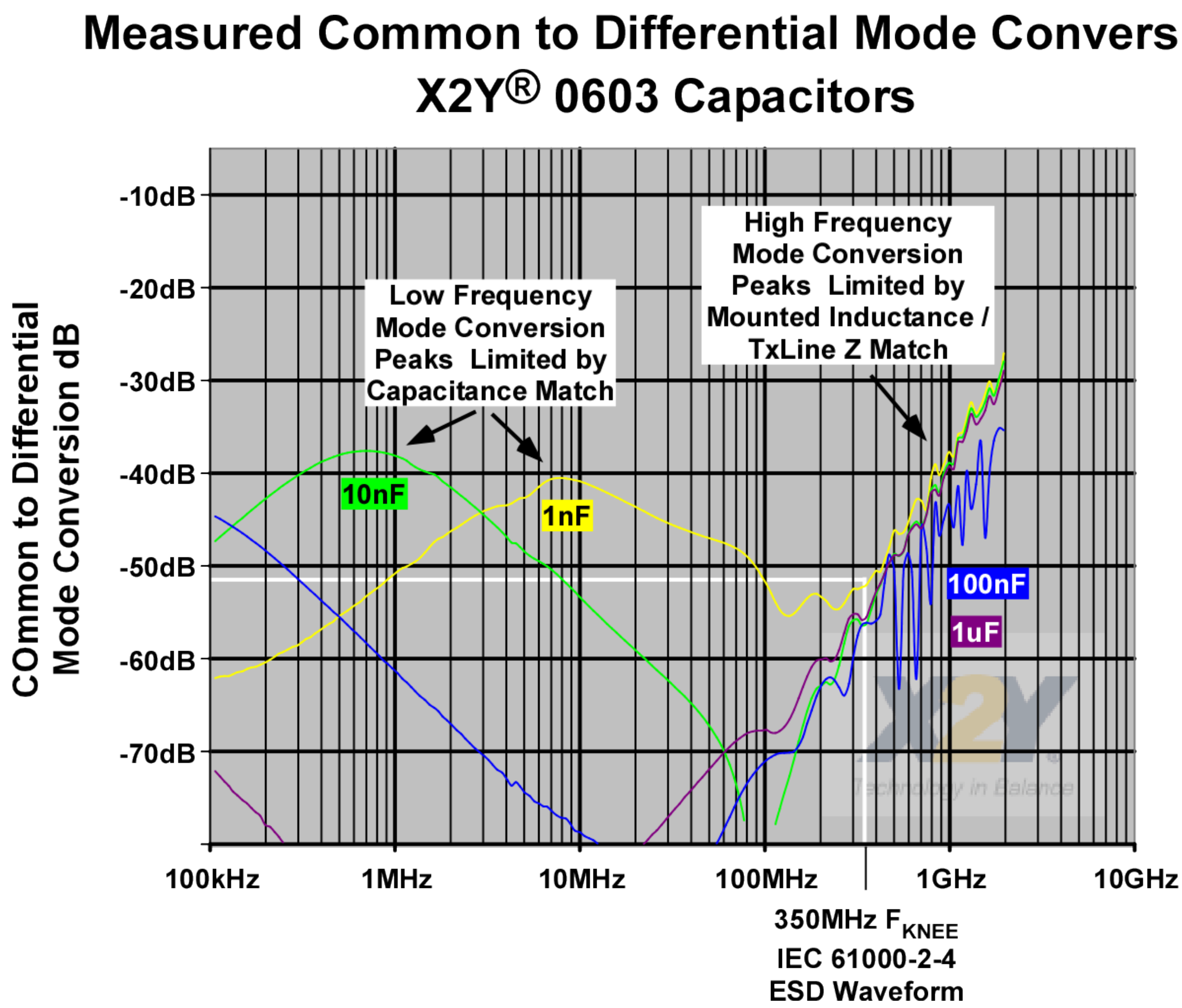
X2Y® ESD SUSCEPTIBILITY




**Measured Common to Differential Mode Conversion**
**X2Y® 0603 Capacitors**

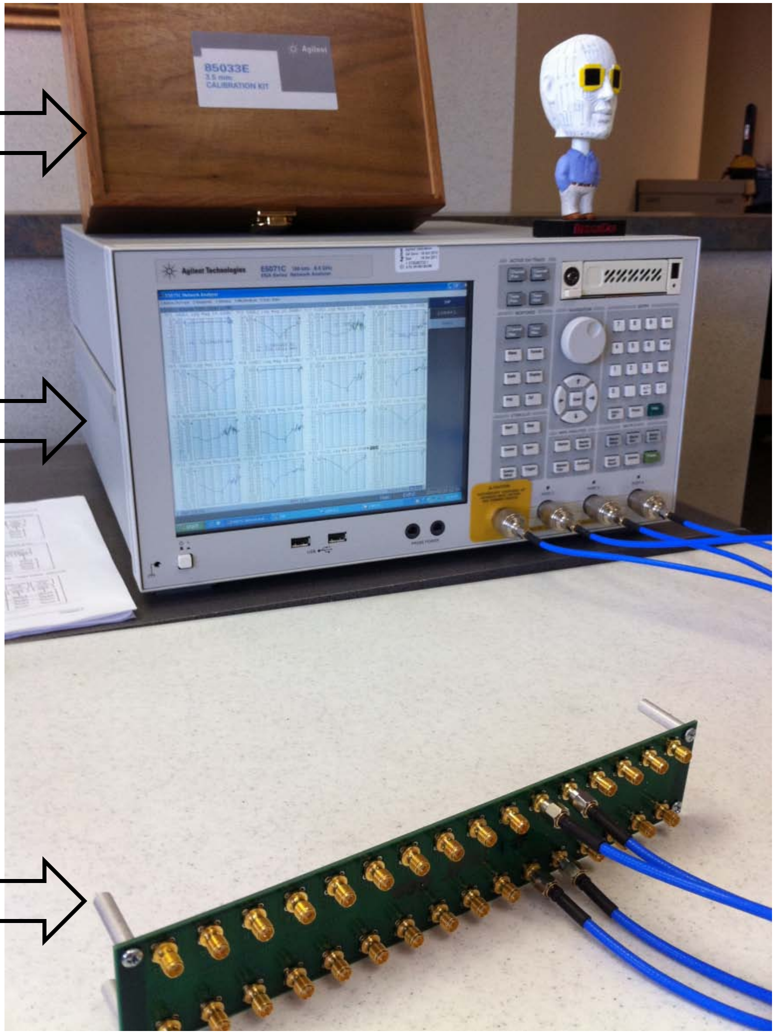


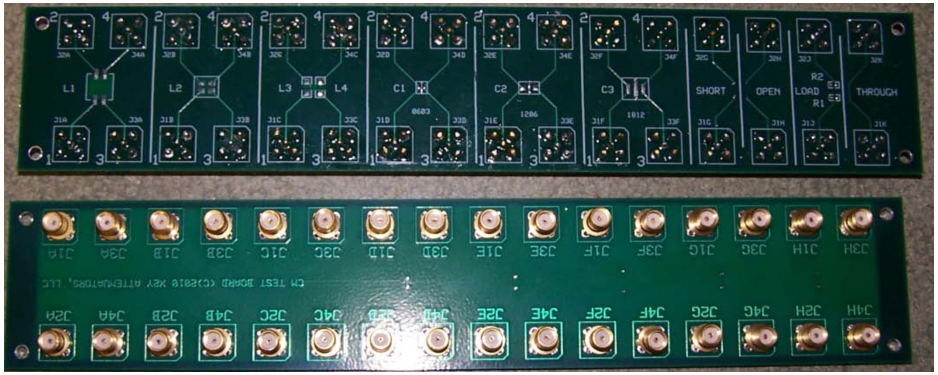
# X2Y® and ESD/EFT Susceptibility



# Test Comparisons

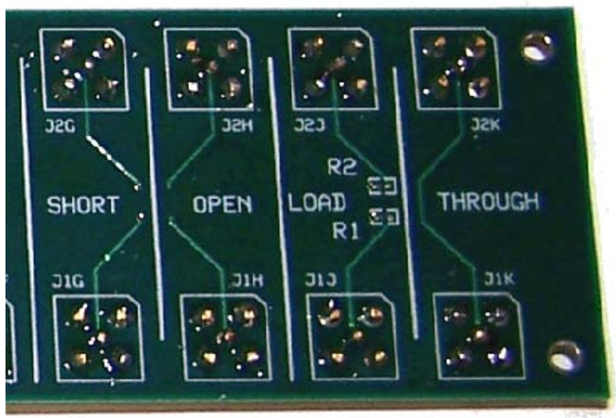
- Test Setup
  - Agilent 85033D 3.5mm Calibration Kit
  - Agilent E5071C ENA Network Analyzer
    - 100 kHz - 8.5 GHz
    - Balanced measurements (4-port option)
  - DUT test board



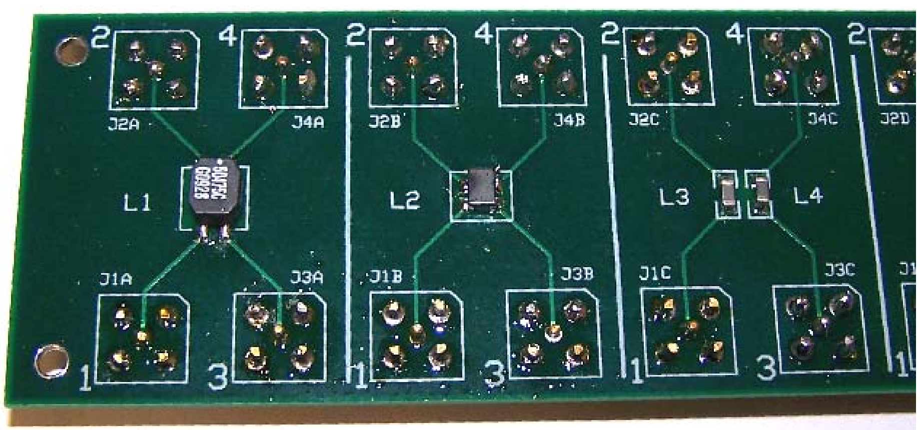
# Test PCBs

Calibration Positions on PCB

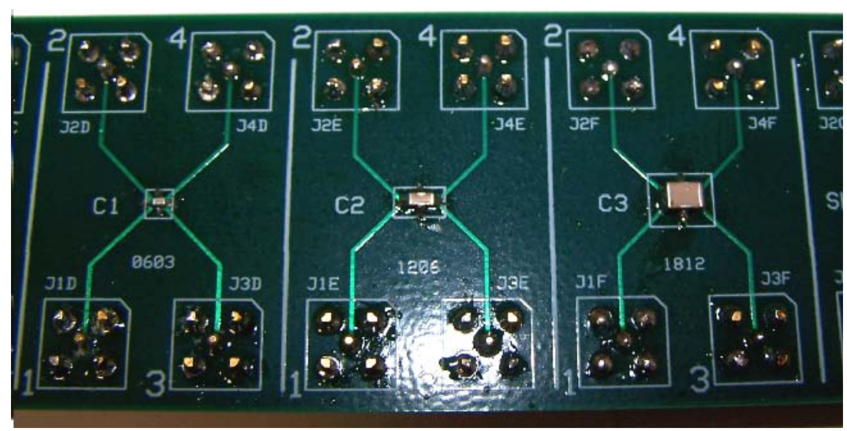



**S**hort/**O**pen/**L**oad/**T**hrough (SOLT) calibration is used to de-embed the test fixture effects.

Inductor DUTs

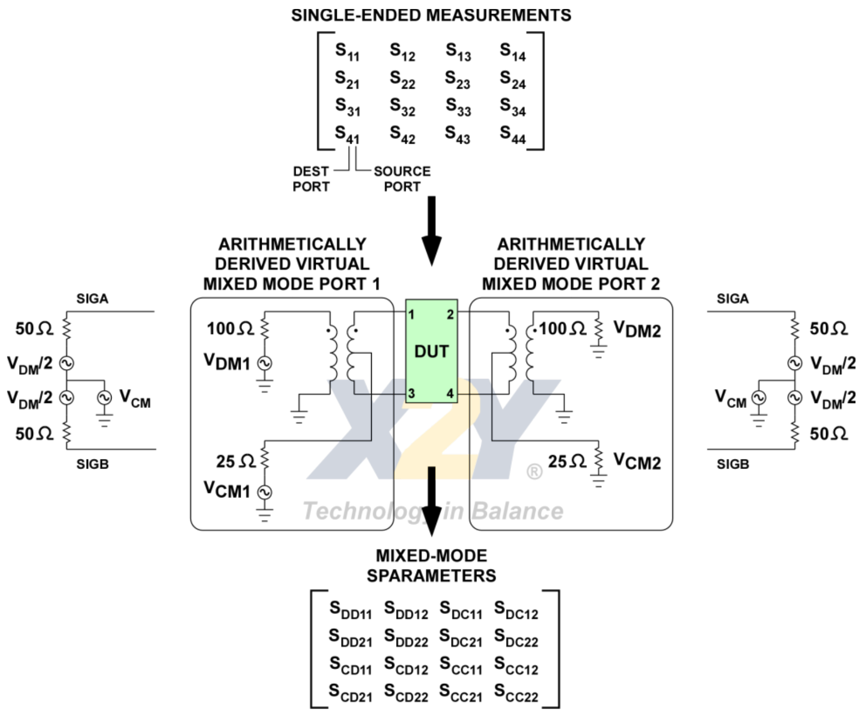



X2Y® Capacitor DUTs

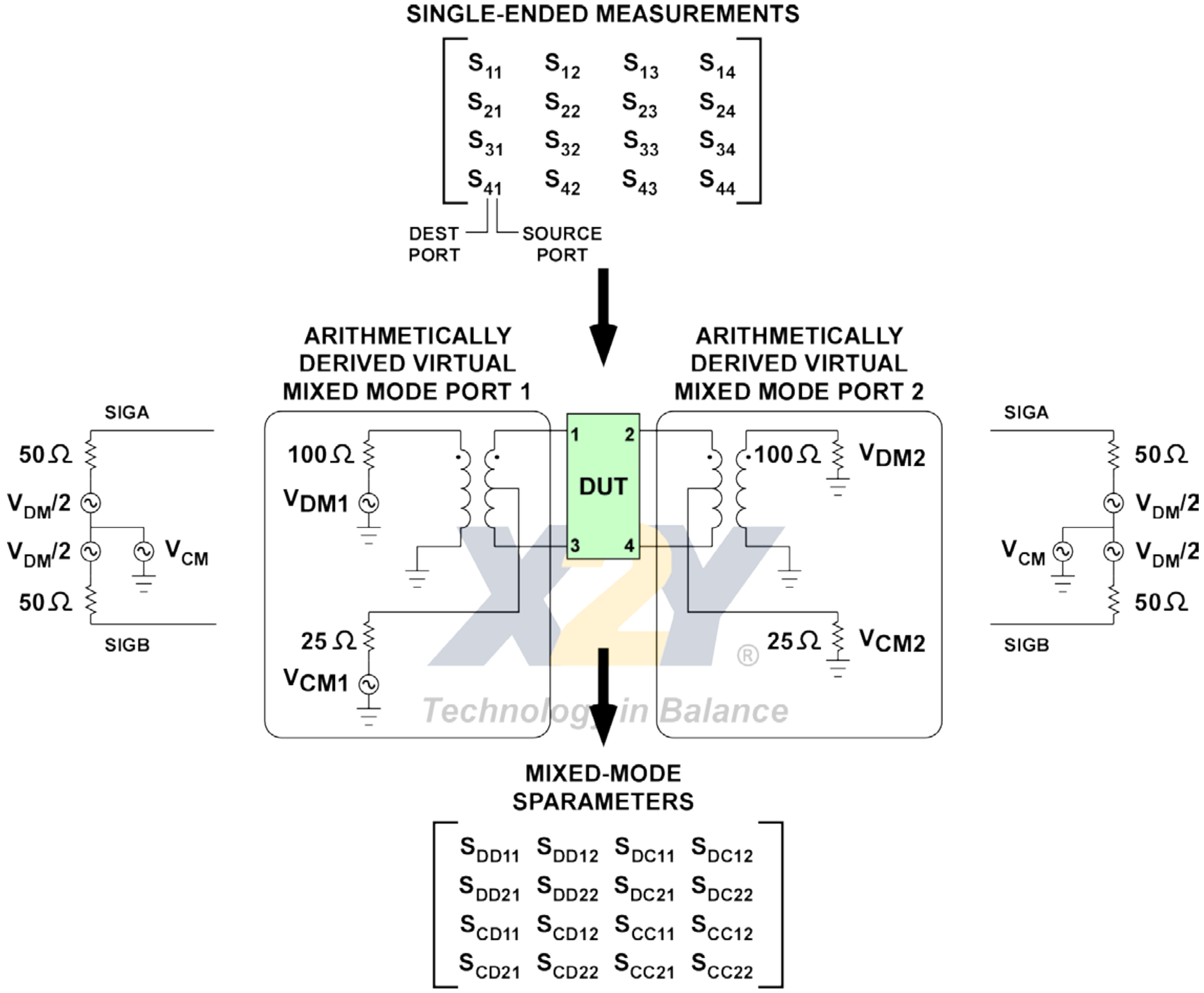


# Mixed-Mode Derivations

- Mixed-mode measurements are derived mathematically from full four-port single-ended VNA measurements.
- The Agilent E5071C VNA includes the matrix manipulation software to perform these transformations.
- Of key importance are:
  - SCC21/SCC12 common mode rejection from one side to the other
    - Measures EMI filter effectiveness
  - SDC21/SDC12 common mode to differention conversion from one side to the other
    - Measures ESD suppression effectiveness

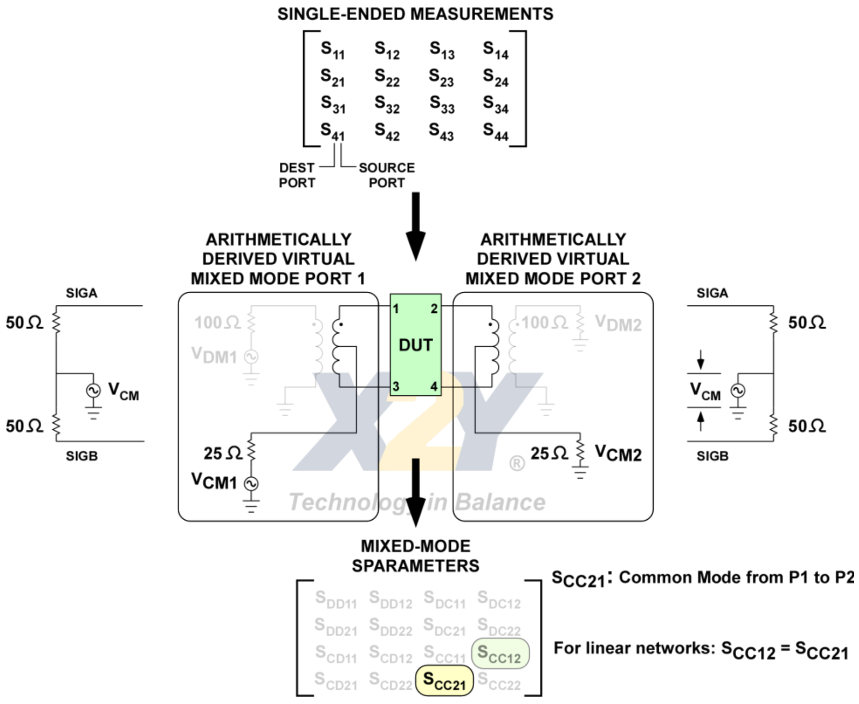


# Mixed-Mode Derivations

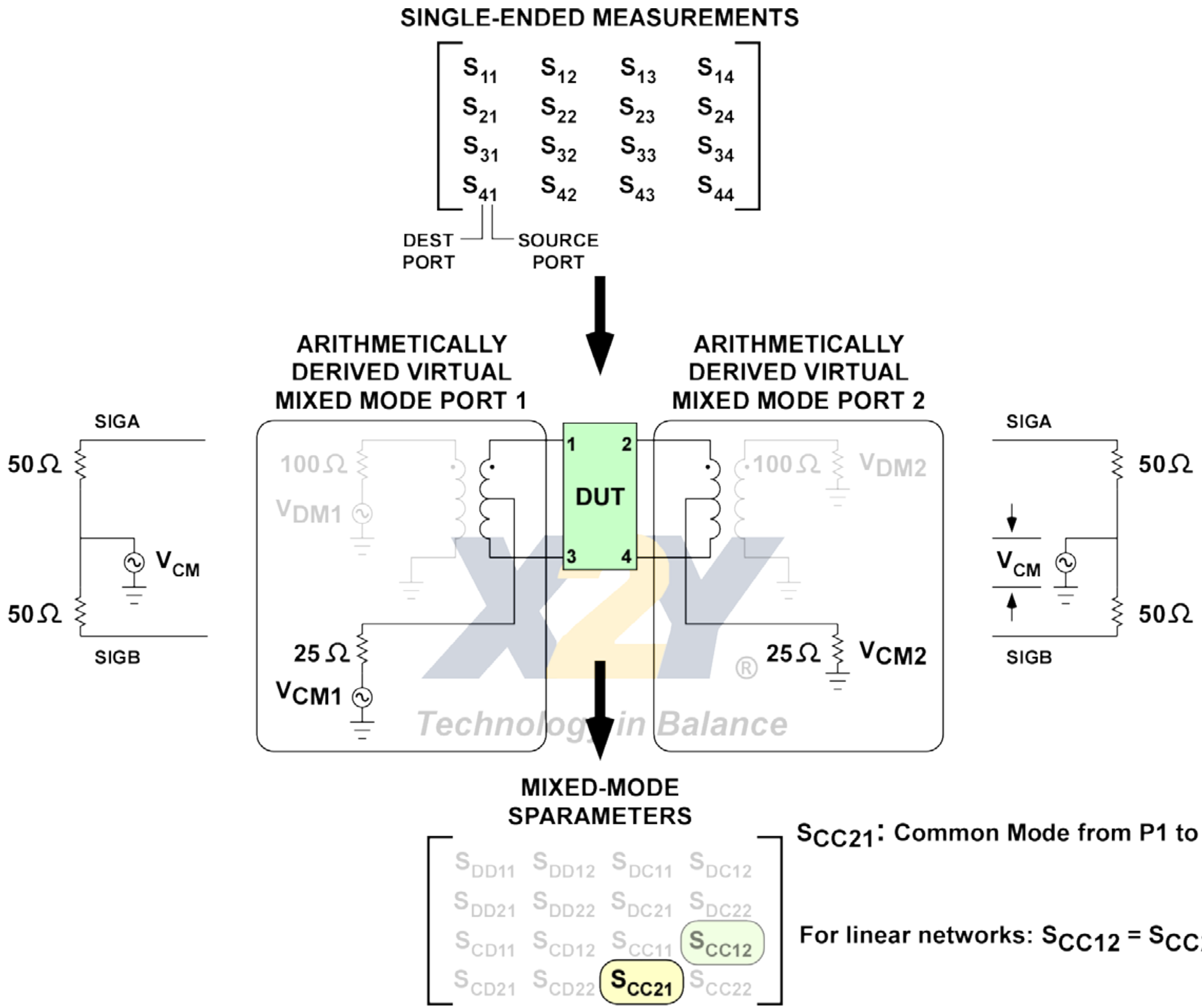


# Common Mode Derivation

- Goal: Determine the amount of common mode energy relative to grond driving Ports 1 and 3 that reaches Ports 2 and 4.
  - Indicates EMI suppression performance
- Both Port 1 and Port 3 drive CM energy in parallel.
  - The two parallel 50Ω ports appear as 25Ω on each side of the filter.
- Operation is symmetric:
  - $S_{CC21}$ matches $S_{CC12}$



# Common Mode Derivation

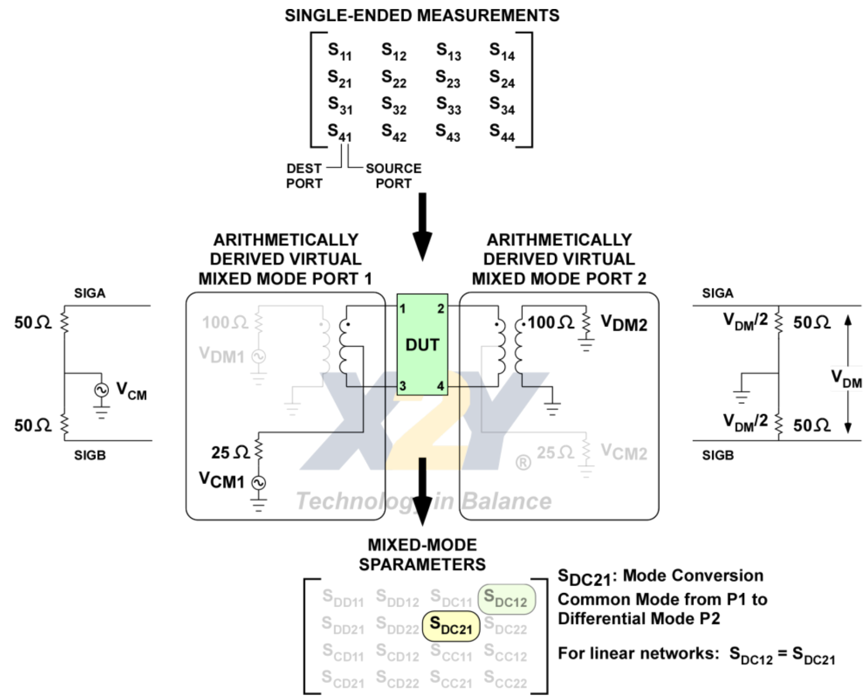



$S_{CC21}$: Common Mode from P1 to P2

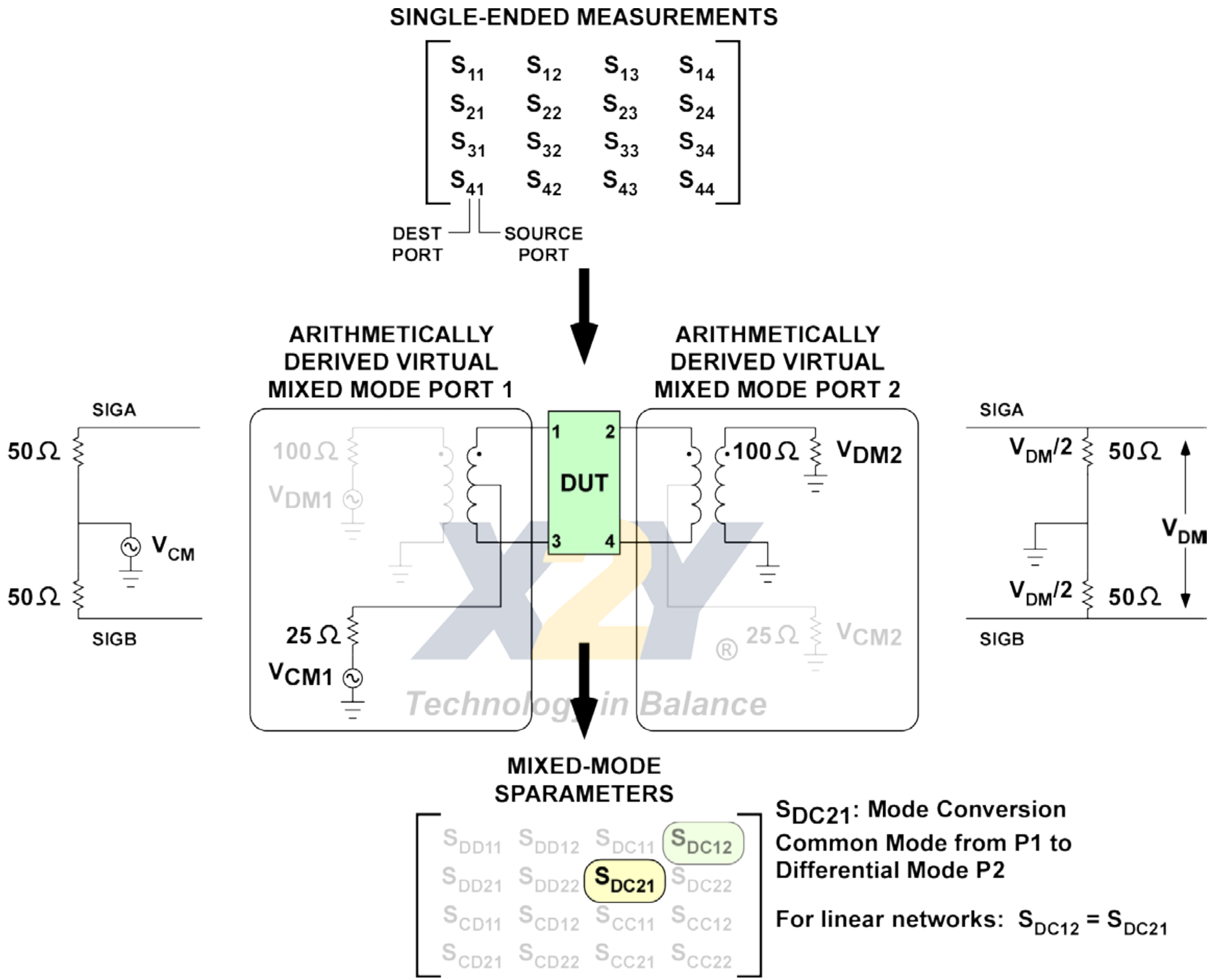
For linear networks: $S_{CC12} = S_{CC21}$

# Common to Diff Mode Conversion Derivation

- Goal: Determine the amount of common mode noise from the external port that converts to differential energy across the internal ports.
  - Indicates immunity to interference: cell phone, ESD, EFT, etc.
- CM input is two parallel 50Ω sources, 25Ω net.
- DM output appears across series 50Ω loads, 100Ω net.
- Operation is symmetric:
  - $S_{DC21}$ matches $S_{DC12}$



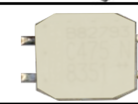
# Common to Diff Mode Conversion Derivation




$S_{DC21}$: Mode Conversion Common Mode from P1 to Differential Mode P2

For linear networks: $S_{DC12} = S_{DC21}$

# DUTs

| DUT | Component Size (mm) | DC Current Rating | Pic |
| --- | --- | --- | --- |
| X2Y® 1812 | 4.4 x 3.2 | In bypass, no current limit |  |
| X2Y® 1206 | 3.2 x 1.6 | In bypass, no current limit |  |
| X2Y® 0603 | 1.6 x 0.8 | In bypass, no current limit |  |
| **(1) 4000 Ohm Common Mode Choke** | 5 .0 x 3.6 | 200 mAmps |  |
| (1) 1000 Ohm Common Mode Choke | 5 .0 x 4.7 | 1500 mAmps |  |
| (1) 4.7 mH Common Mode Choke A | 9.0 x 6.0 | 400 mAmps |  |
| **(1) 4.7mH Common Mode Choke B** | 9.3 x 5.9 | 400 mAmps |  |
| **(2) 1uH Chip Inductors** | (2) 3.2 x 1.6 | 1200 mAmps |  |
| (2) 120 Ohm Ferrite beads | (2) 3.2 x 1.6 | 3000 mAmps |  |
| **(2) 600 Ohm Ferrite beads** | (2) 3.2 x 1.6 | 3000 mAmps |  |

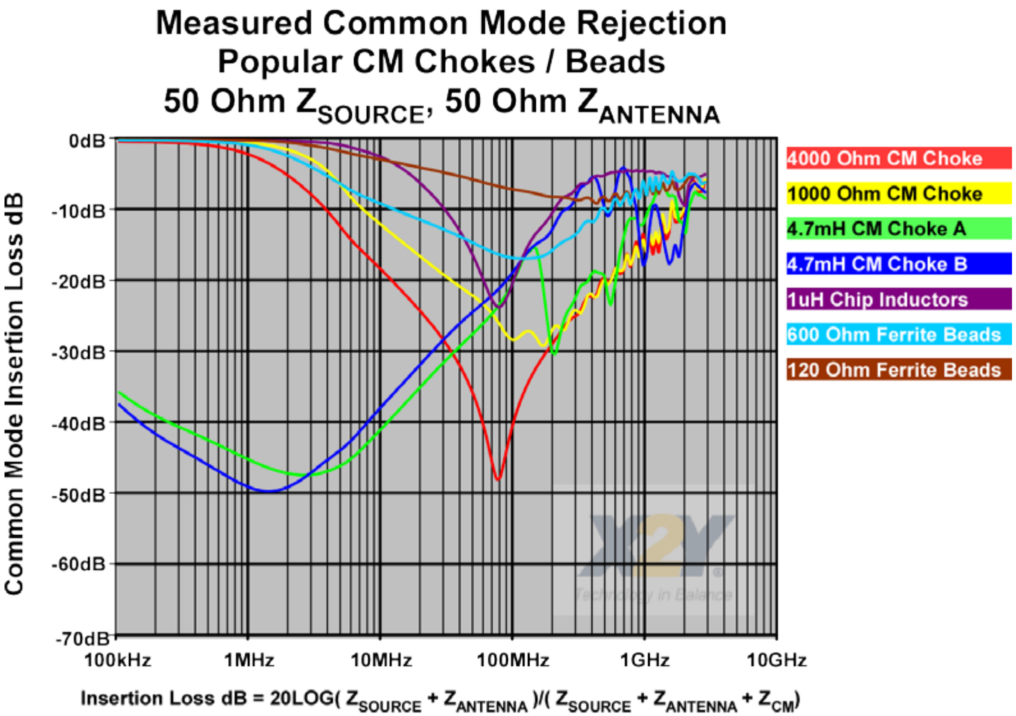
# Footprint Comparisons

X2Y® CAPACITORS SUPERIMPOSED OVER MAGNETIC CM FILTERS

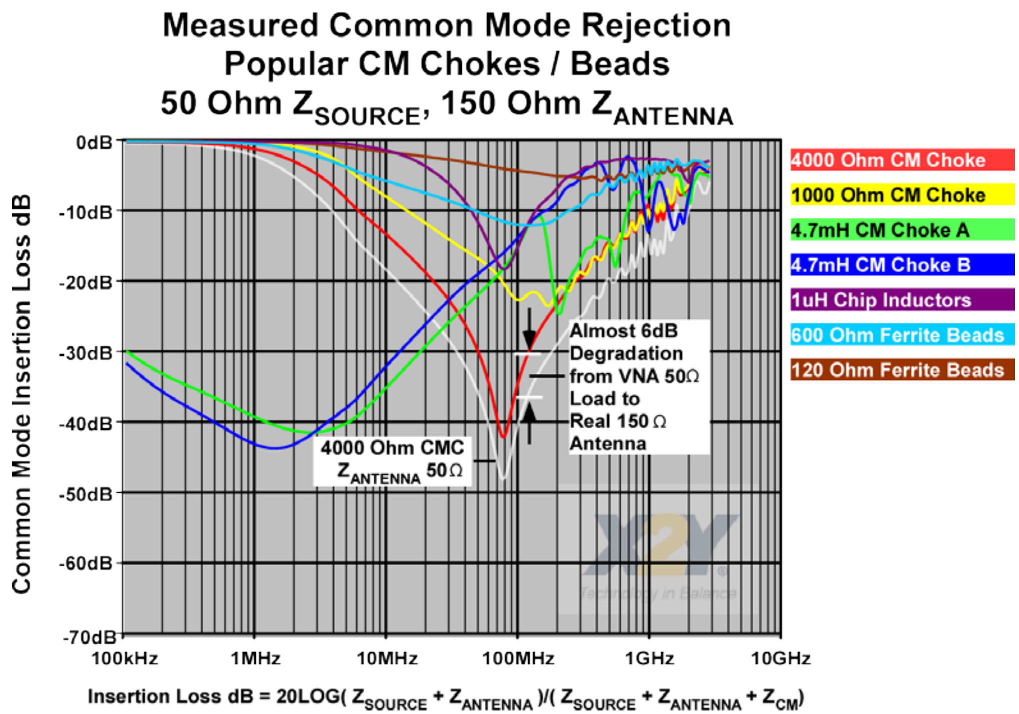
# Common Mode Rejection Performance

- CM Rejection at frequencies > 100MHz is generally weak with magnetics
  - Interwinding capacitance bypasses series inductance at high frequencies.
  - Ferrite interdomain capacitance bypasses series loss at high frequencies.



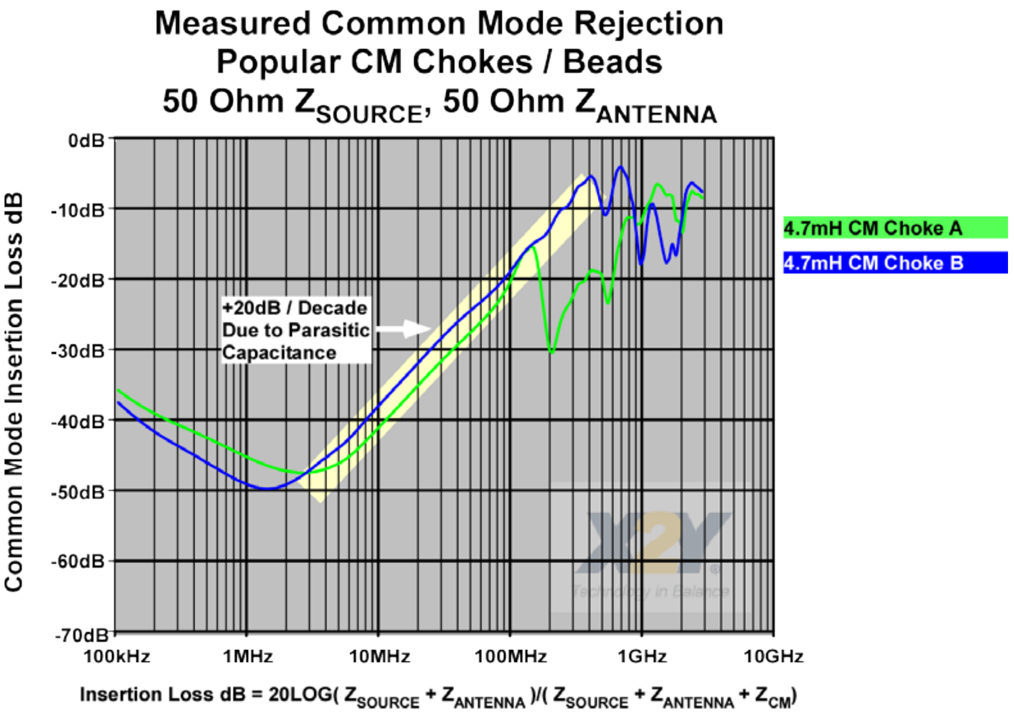
# Common Mode Rejection Performance

- Rejection ratio degrades for real antenna Z > 50Ω
  - 120 – 180 Ohms typical
  - 150Ω degrades by
    - 6dB at high loss,
    - ≈ 3dB near 10dB
- Where $Z_{CM} >> ( Z_S+Z_A)$:
  - Loss ≈ $20LOG(Z_S + Z_A)/(Z_{CM})$
  - Increasing $Z_A$ from 50 to 150 doubles $(Z_S + Z_A)$



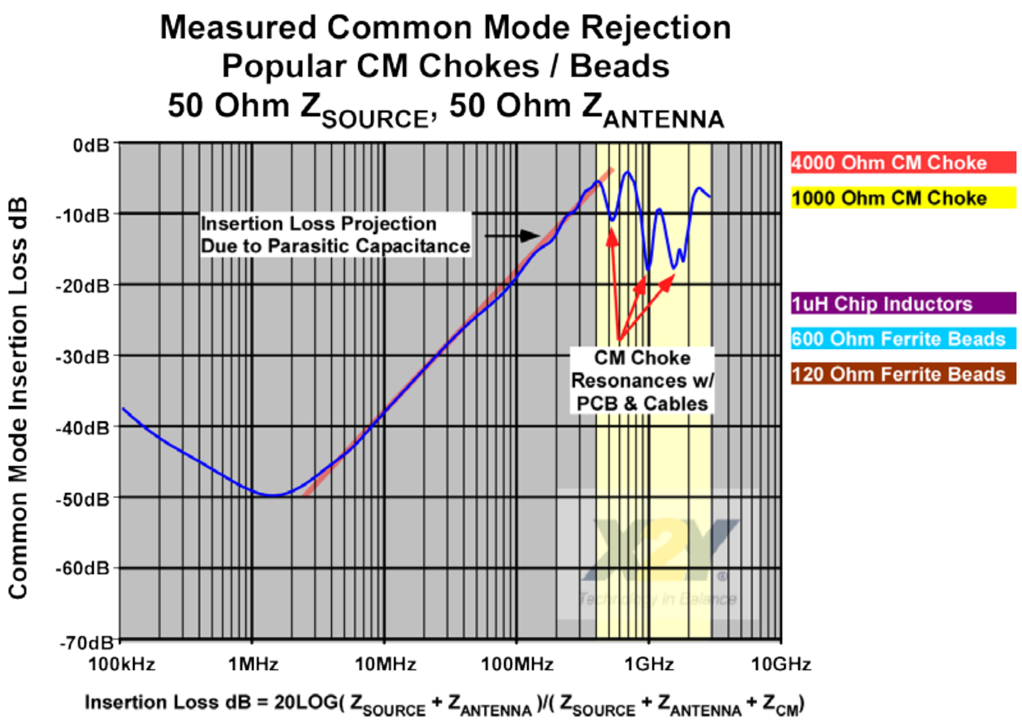
# Common Mode Rejection Performance

- Low frequency chokes:
  - Capable of good insertion loss at modest frequencies.
  - Capacitive parasitics reduce attenuation to 20dB or less @ 100MHz
- Resonances create unstable insertion loss @ high frequencies.
  - Actual insertion loss highly dependent on:
    - Circuit source impedance
    - Cable geometry



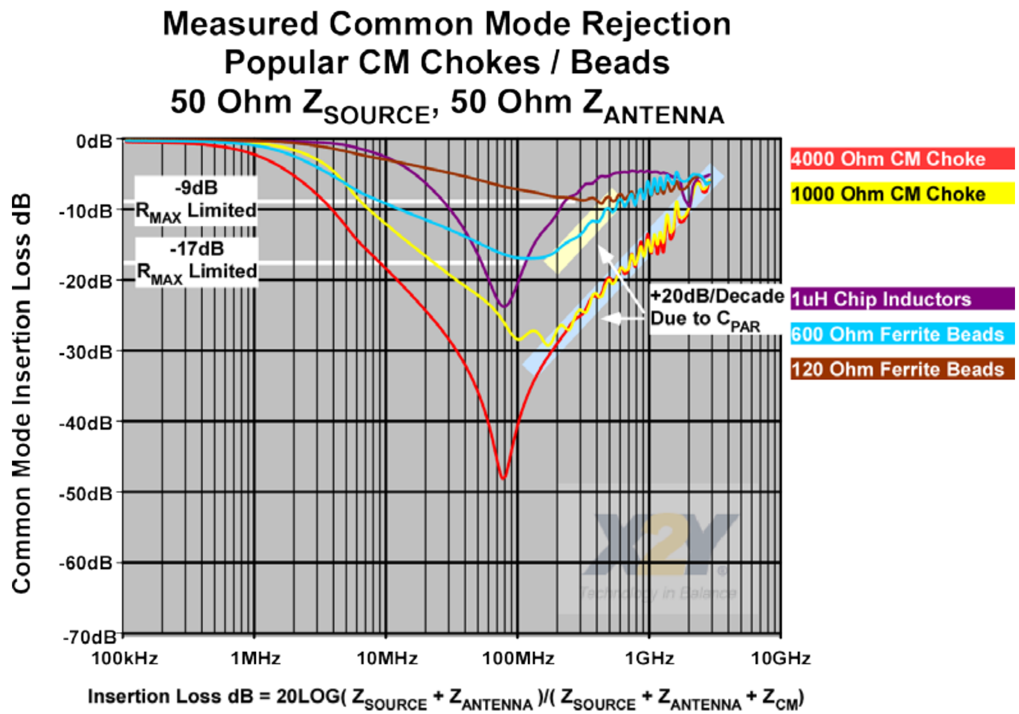
# Common Mode Rejection Performance

- Complex HF resonances
  - High inductance / capacitance chokes exhibit complex interactions with PCB traces, connectors, & cables @ high frequencies.
  - As frequency moves between odd and even 1/4λ multiples of cable lengths, unterminated cable noise attenuation moves between local minima and maxima.



# Common Mode Rejection Performance

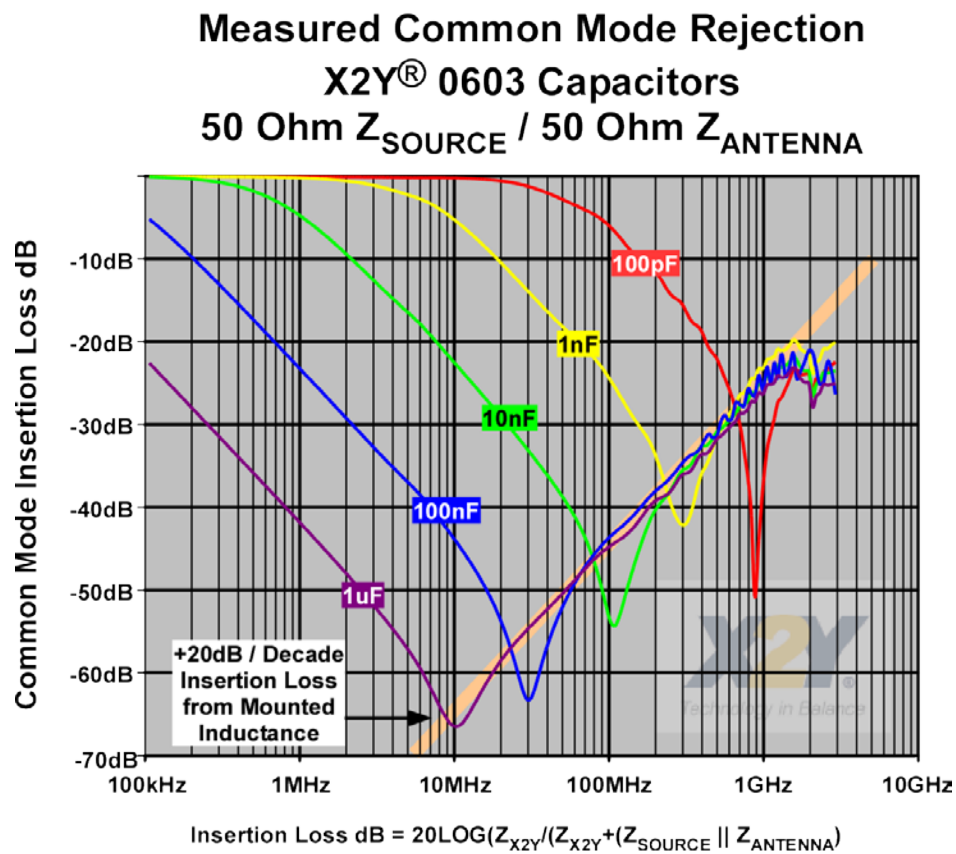
- High frequency chokes / beads
  - Bead insertion loss limited by parasitic resistance and capacitance.
  - 600 Ohm bead limits max. insertion loss to -17dB
  - 1pF limits insertion loss @ 1GHz to -8dB
    - Must include PCB parasitics
    - Nearby etch or parts can destroy HF insertion loss



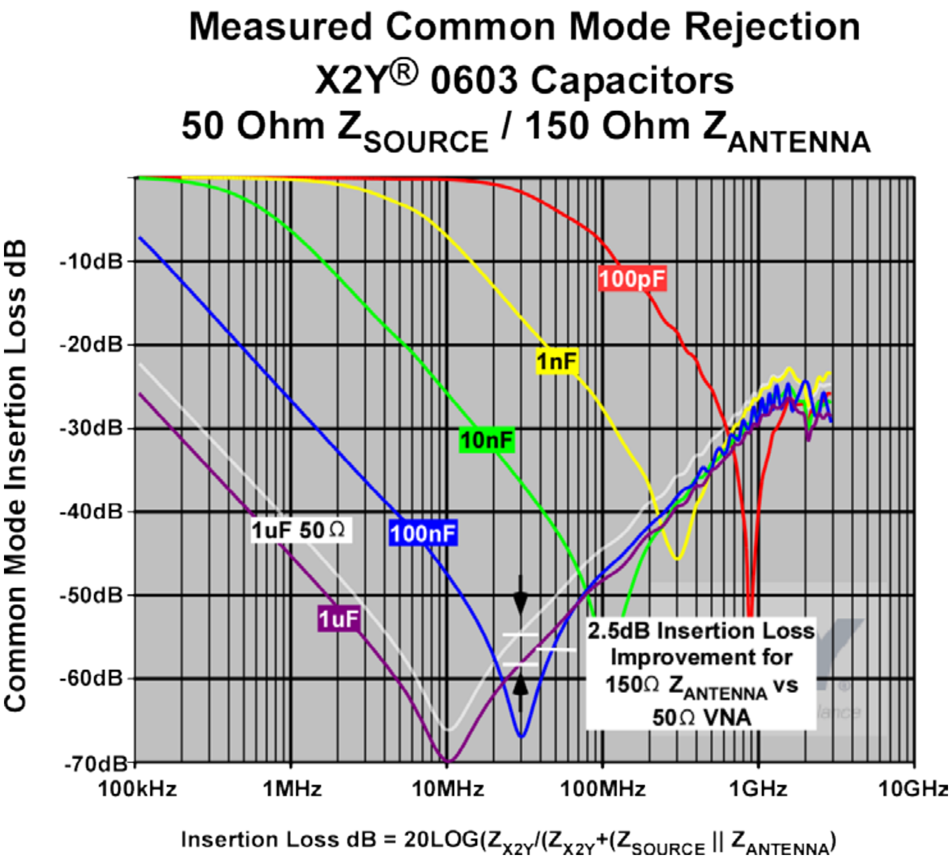
# Common Mode Rejection X2Y®

- Consistent high frequency performance independent of capacitance.
  - Mounted inductance controls
  - Linear decrease in noise attenuation w/frequency
  - 0603 parts -24dB or better @ 1GHz into 25 Ohm even mode impedance.
- Capacitor value only affects low frequency attenuation.
  - Larger capacitance values filter lower frequencies

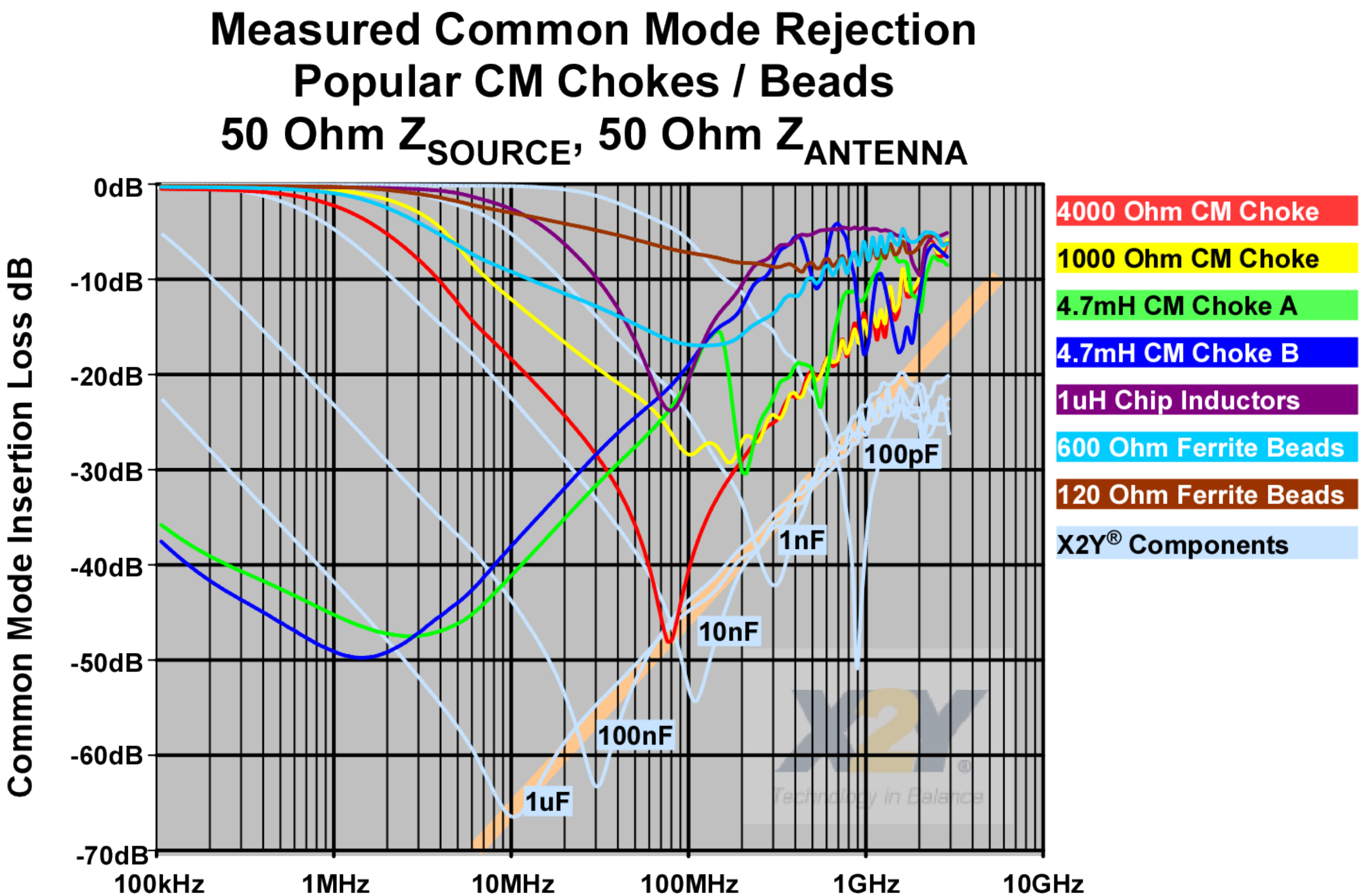


# Common Mode Rejection X2Y®

- Rejection ratio improves for real antenna Z > 50Ω
  - 120Ω – 180Ω Ohms typical
  - 150Ω improves by
    - 2.5dB at high loss, (>20dB)
- Where $Z_{X2Y}$ << ( $Z_S$||$Z_A$):
  - Loss ≈ 20LOG($Z_{X2Y}$)/($Z_S$||$Z_A$)
  - Increasing $Z_A$ from 50Ω VNA port to 150Ω practical antenna value decreases ($Z_S$||$Z_A$) by 0.75:1.

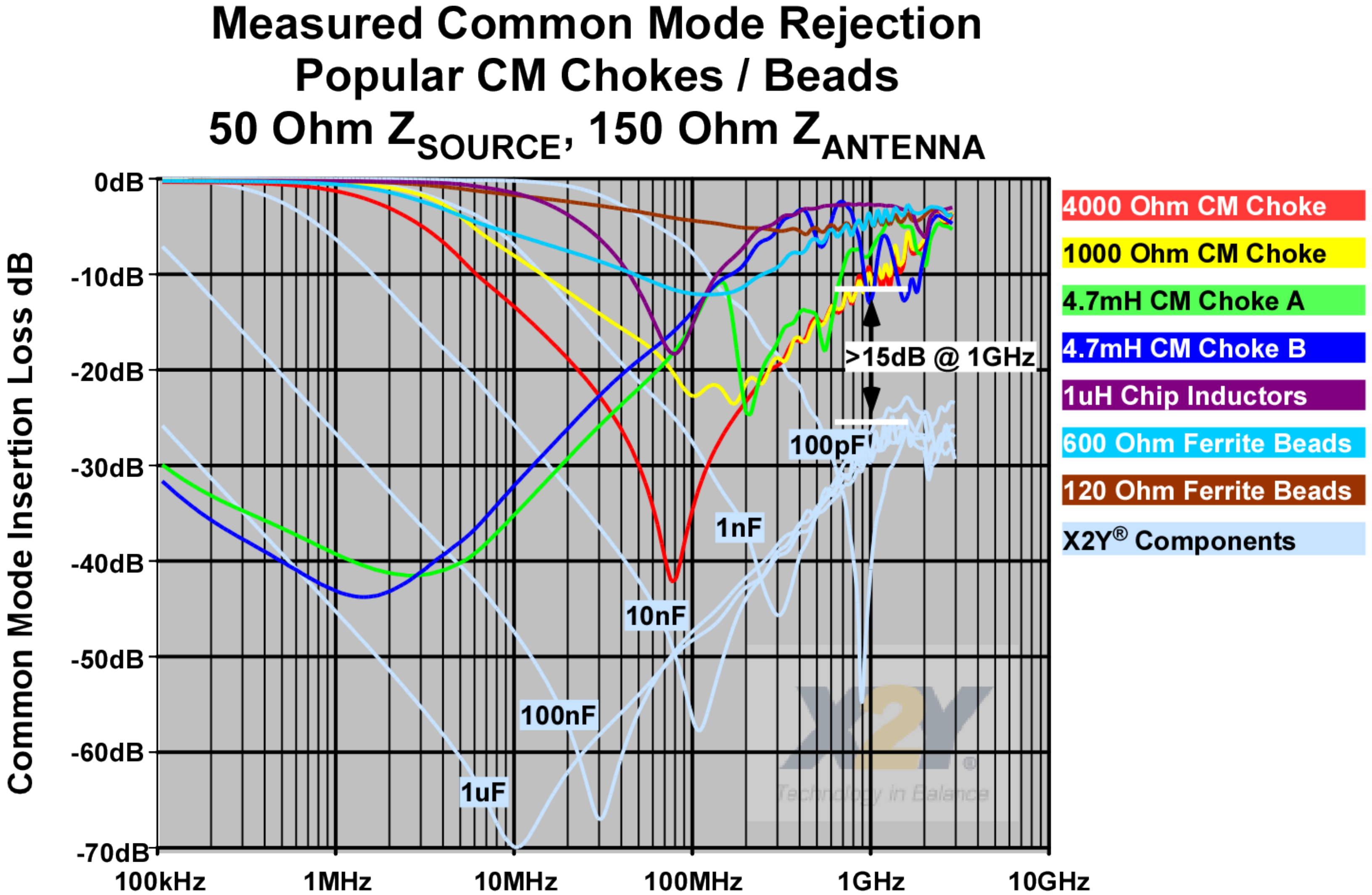


# Common Mode Rejection Comparisons




Insertion Loss dB = 20LOG( $Z_{SOURCE}$ + $Z_{ANTENNA}$ )/( $Z_{SOURCE}$ + $Z_{ANTENNA}$ + $Z_{CM}$)

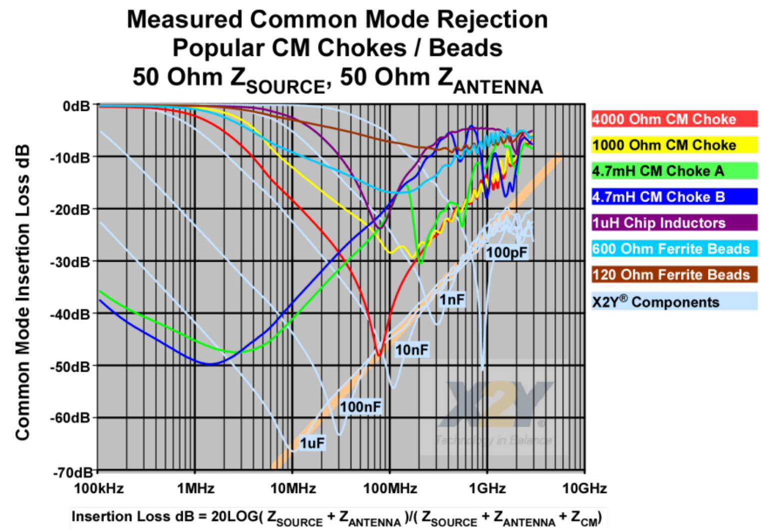
# Common Mode Rejection Comparisons

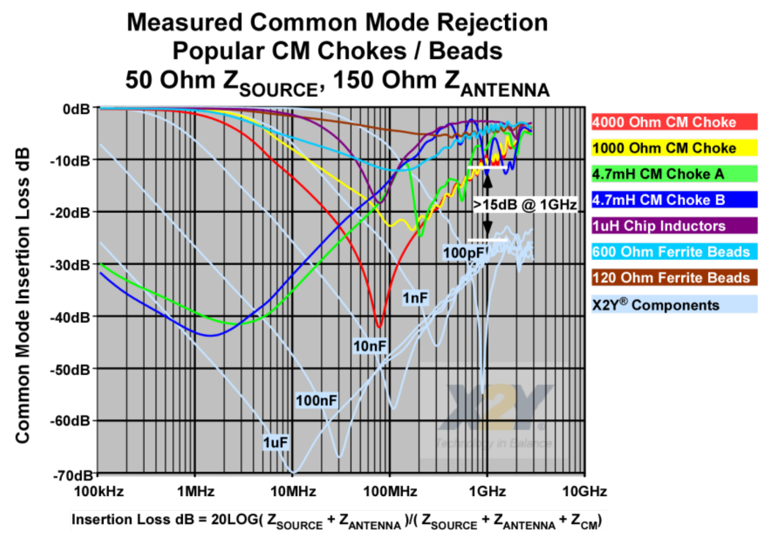



Insertion Loss dB = 20LOG( $Z_{SOURCE} + Z_{ANTENNA}$ )/( $Z_{SOURCE} + Z_{ANTENNA} + Z_{CM}$)

# Common Mode Rejection Comparisons Load Antenna Impedance

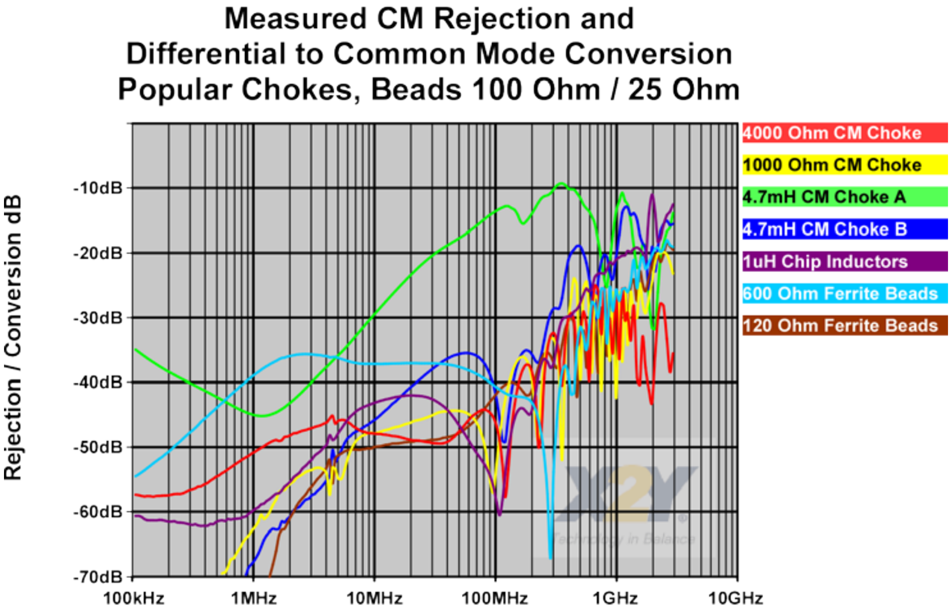
- X2Y® capacitors significantly outperform CM chokes using 50Ω VNA ports
- X2Y® capacitors exhibit even greater advantage in real applications using typical 150Ω antennae.



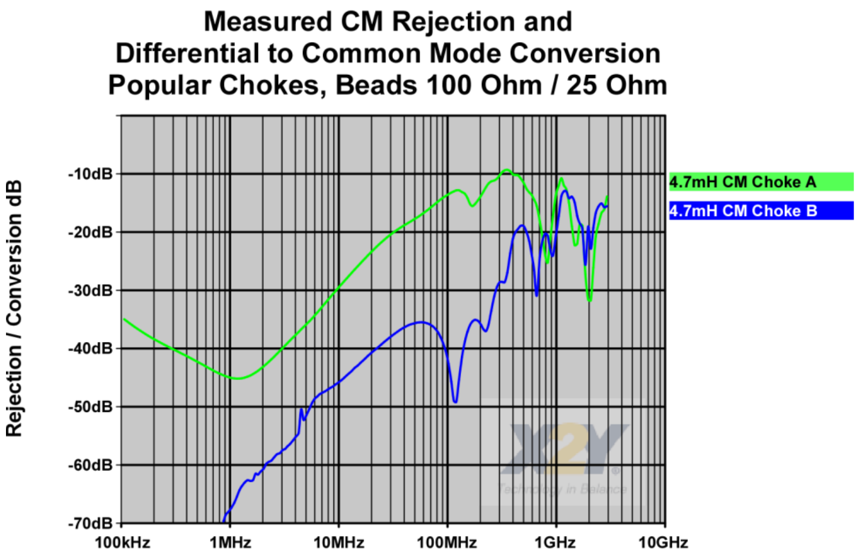
# Differential to Common Mode Conversion Measurements

- Parasitic capacitive coupling in CM chokes results in significant mode conversion at even modest frequencies.
  - Typical ≈ -35dB @ 350MHz ($F_{KNEE}$ IEC 61000-2-4)
  - Some devices are much worse
- Results in weak ESD immunity.



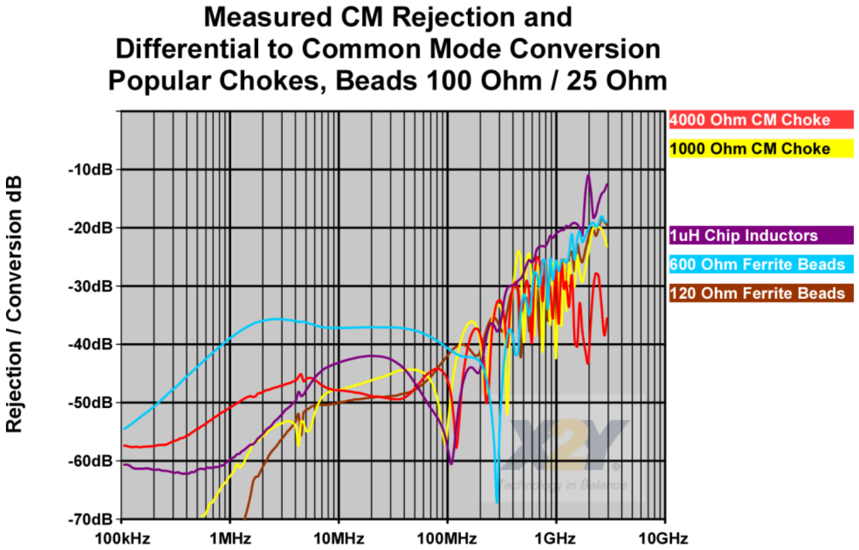
# Differential to Common Mode Conversion Measurements

- Different chokes with the same datasheet specifications can result in dramatically different mode conversion characteristics.
- LF chokes exhibit particularly poor mode conversion at high frequencies.



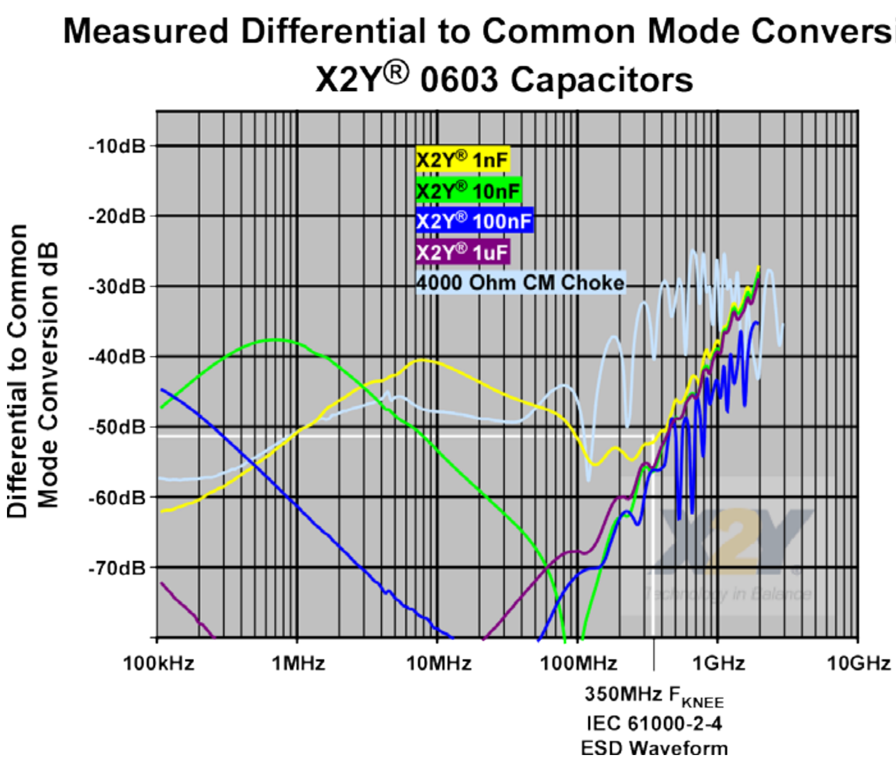
# Differential to Common Mode Conversion Measurements

- Ferrite beads and smaller value chokes improve mode conversion, but exhibit poorer common mode rejection



# Differential to Common Mode Conversion Measurements

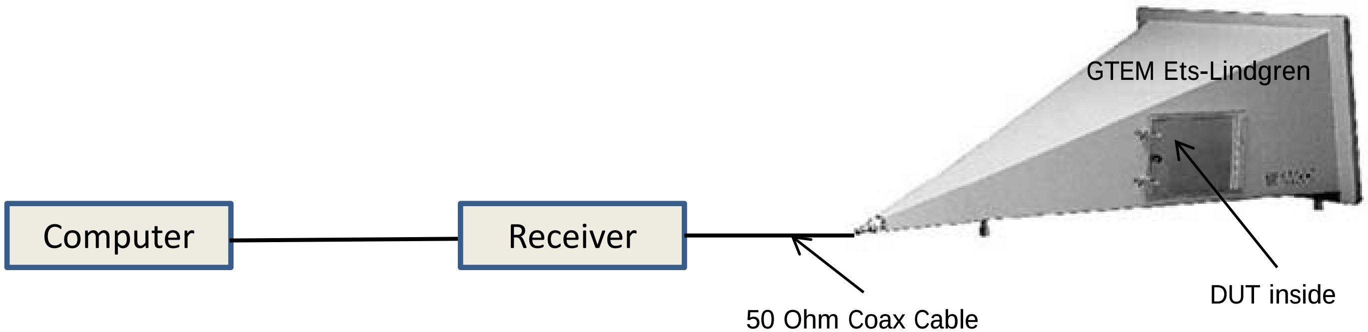
- X2Y® capacitors convert a small amount of differential energy to common mode due to finite tolerance mismatches.
- Conversion is -52dB @ 350MHz, -40dB @1GHz
  - 17dB better than typical CM choke / bead solution



# Test Comparisons

- Example, Single Board Computer Power Feed:
  - 68HC11 processor
- 5uH CM choke tested
- PI filter w/ 5uH CM choke tested
  - 0.1uF cap_5uH CM choke_220nF cap
- Seven values of X2Y® capacitors tested
  - 47pF, 100pF, 220pF, 330pF, 470pF, 560pF, 1000pF

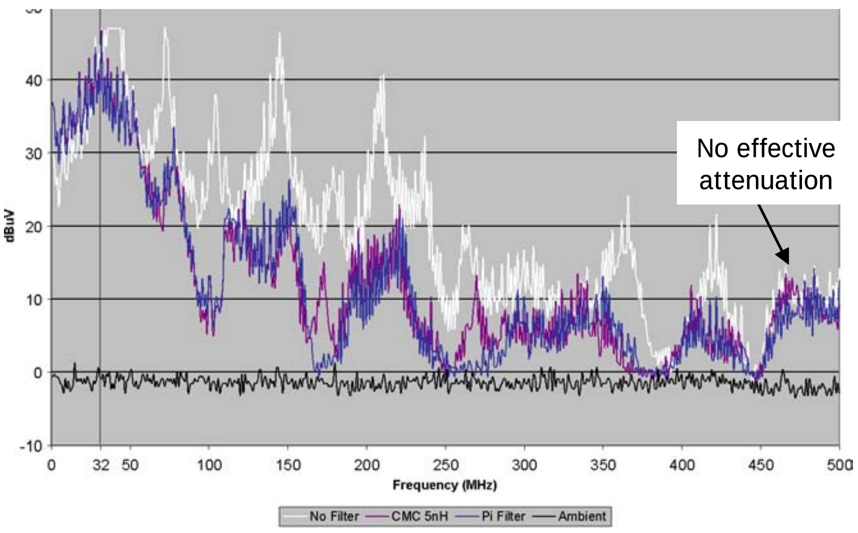
- Radiated Emissions Setup:



# Comparative Performance Application

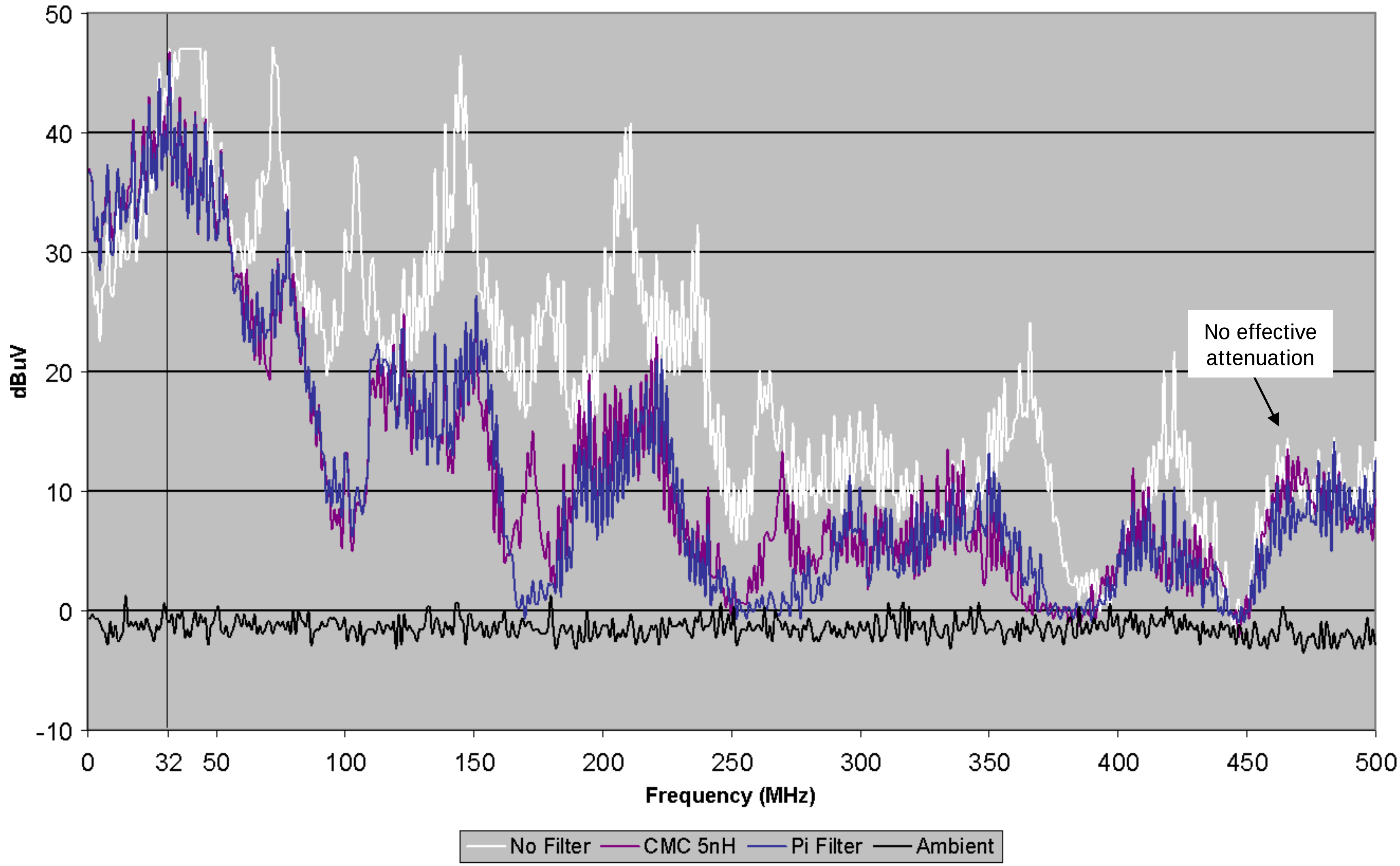
- CM Choke and PI filters both exhibit similar performance
  - Filter cut-off ≈ 32MHz
  - Attenuation effective to about 450MHz
- Parasitic capacitance completely defeats CM choke and PI filter above 450MHz

HC11 (1MHz – 500MHz, CMC and PI)



# Comparative Performance Application

HC11 (1MHz – 500MHz, CMC and PI)



# Comparative Performance Application

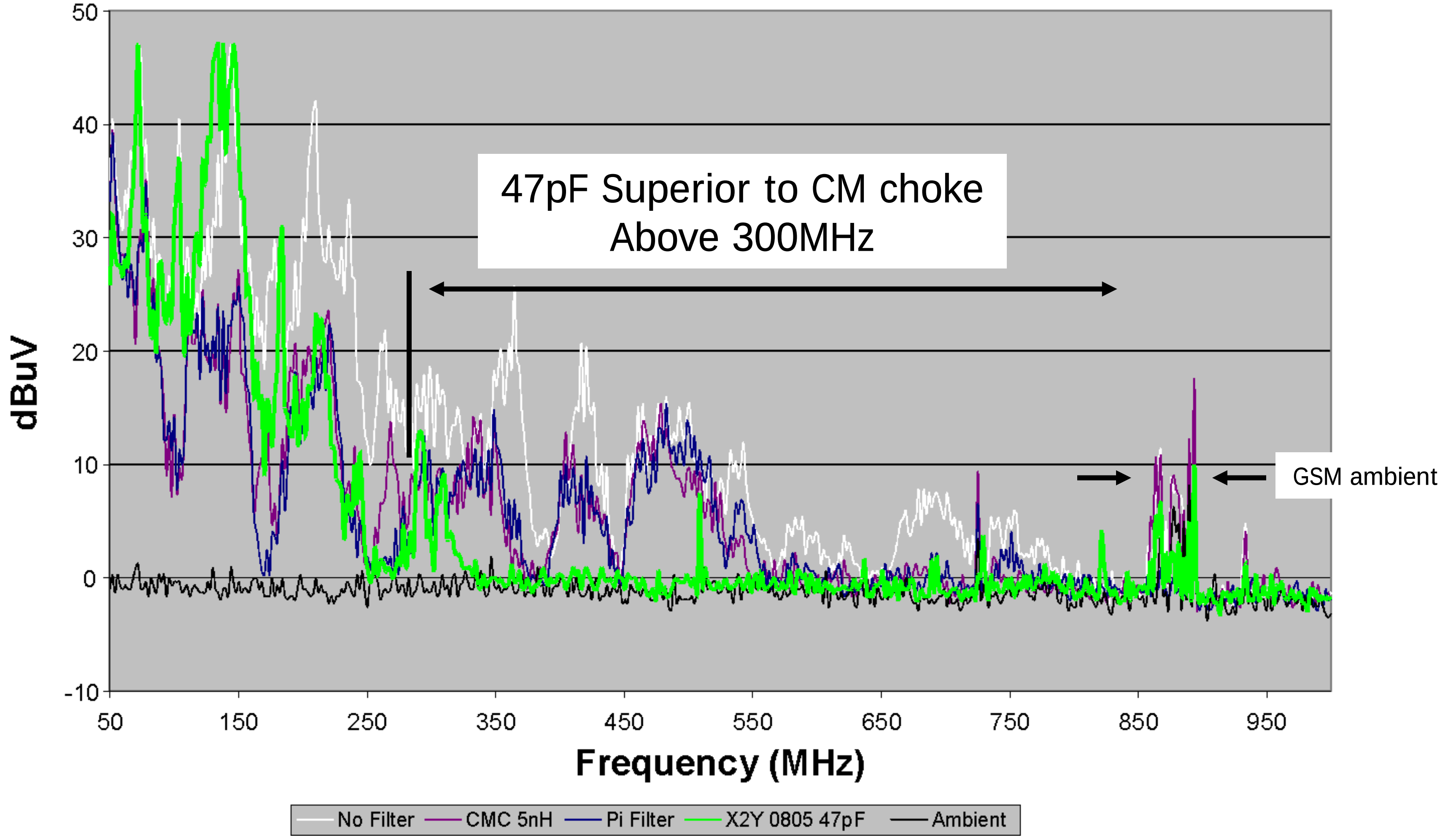
Slides 37-44, 50MHz –1GHz:

- X2Y® capacitors effective to 1GHz and beyond.
- Capacitance value determines low frequency rejection.
- Very small X2Y® caps (47pF) superior solution vs. CM chokes or PI filters down to 300MHz.
- 470pF and larger X2Y® caps superior over all frequencies.

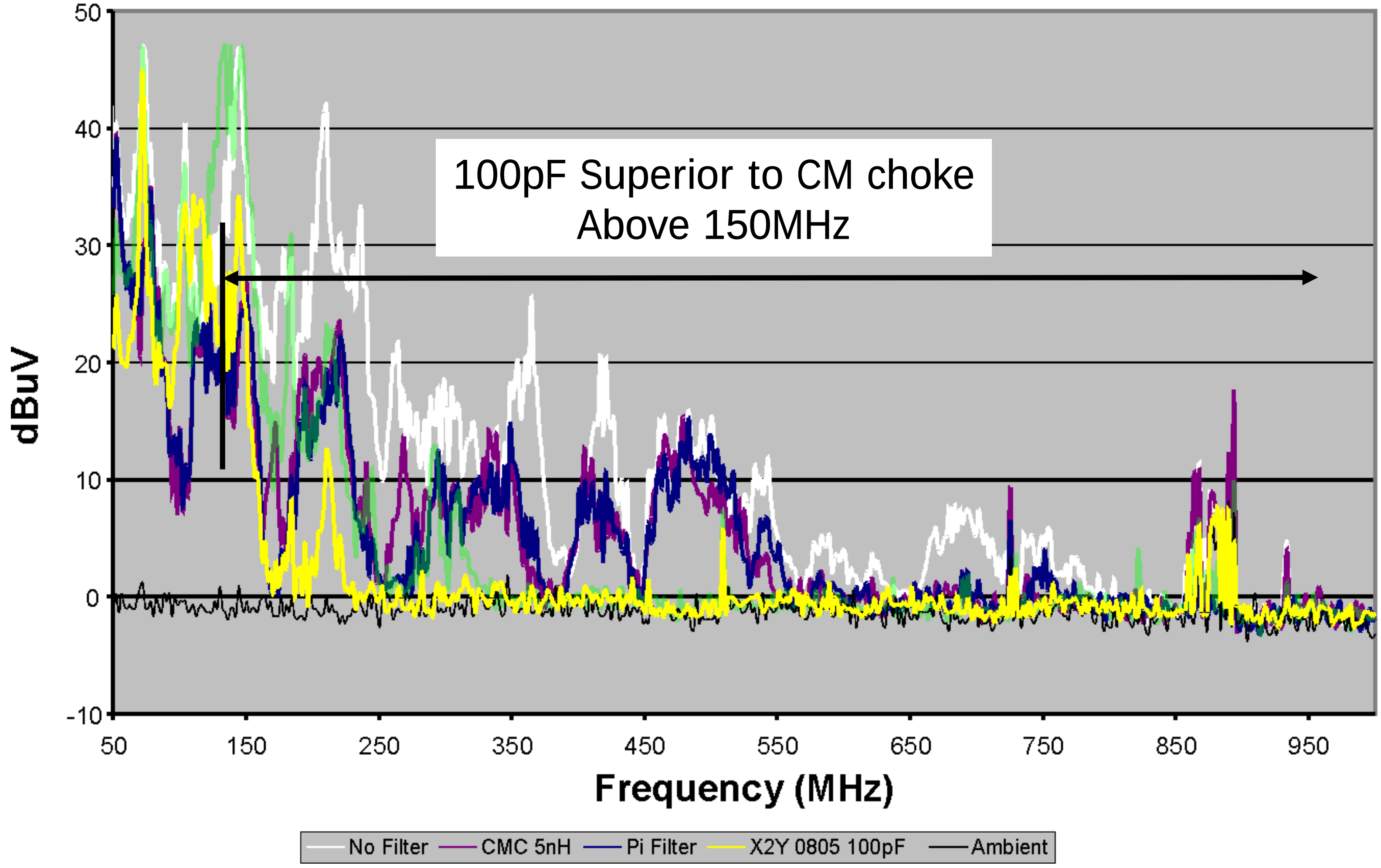
# Comparative Performance Application

HC11 (50MHz –1GHz, 47pF X2Y)



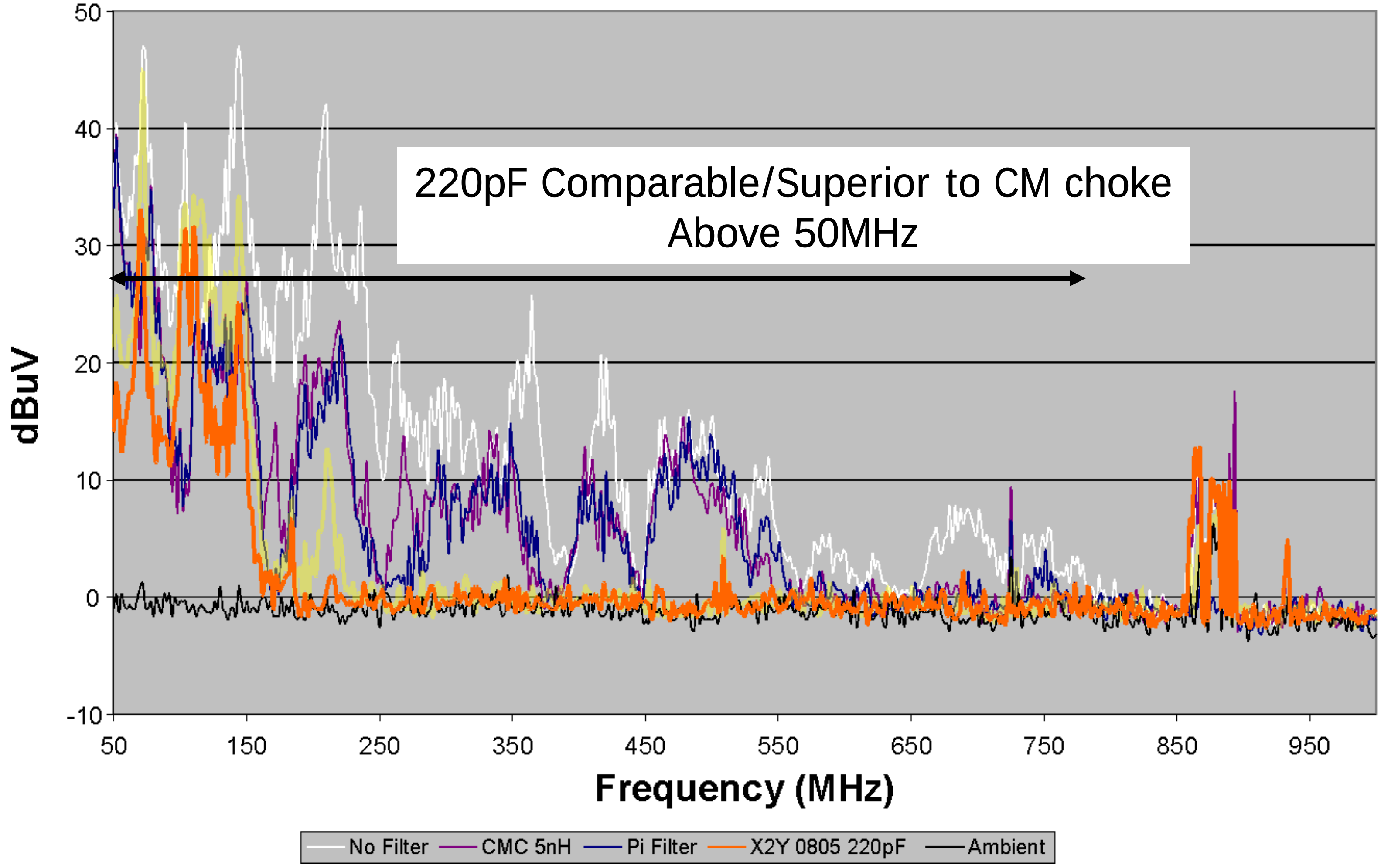
# Comparative Performance Application

HC11 (50MHz –1GHz, 100pF X2Y)



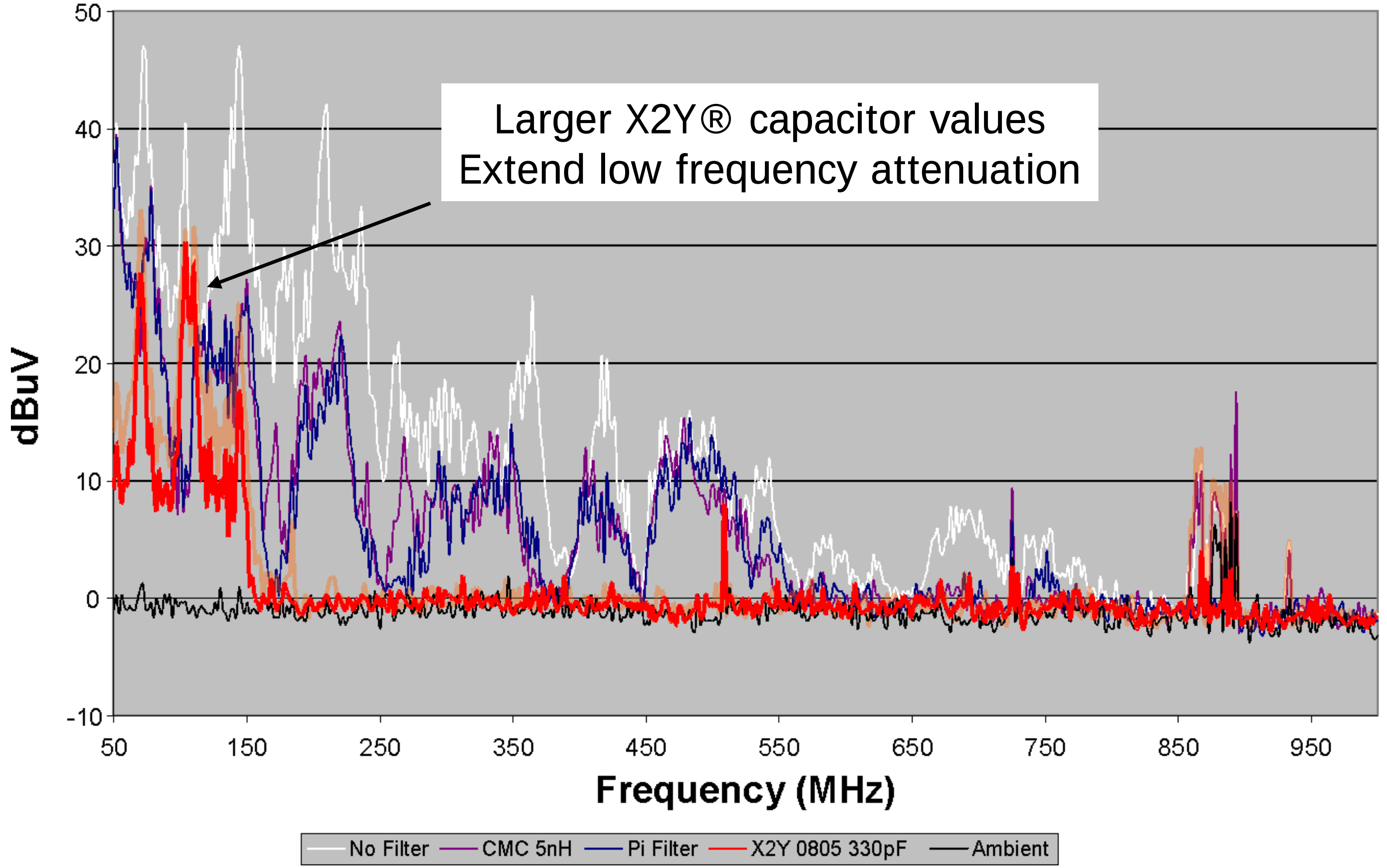
# Comparative Performance Application

HC11 (50MHz –1GHz, 220pF X2Y)

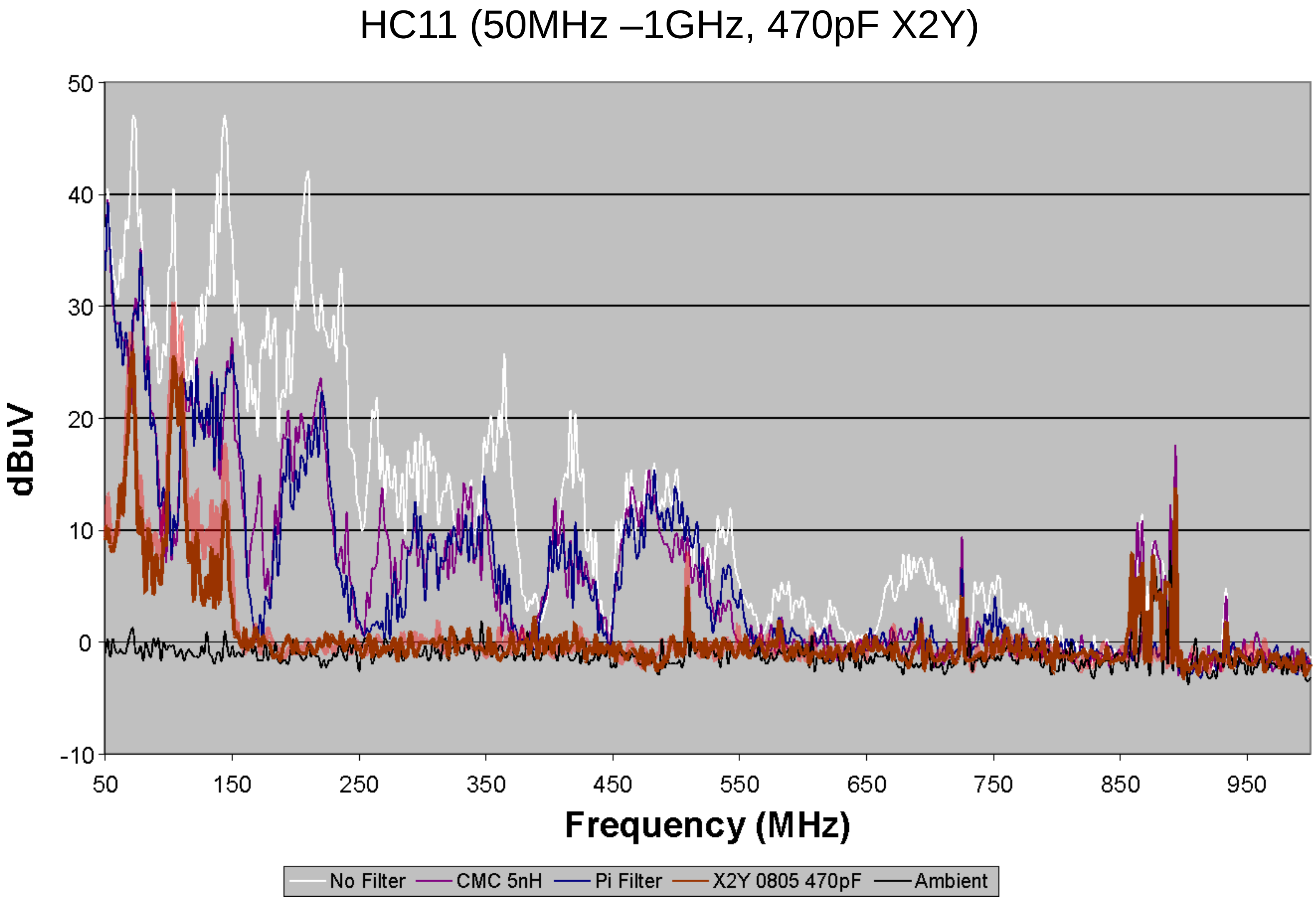


# Comparative Performance Application

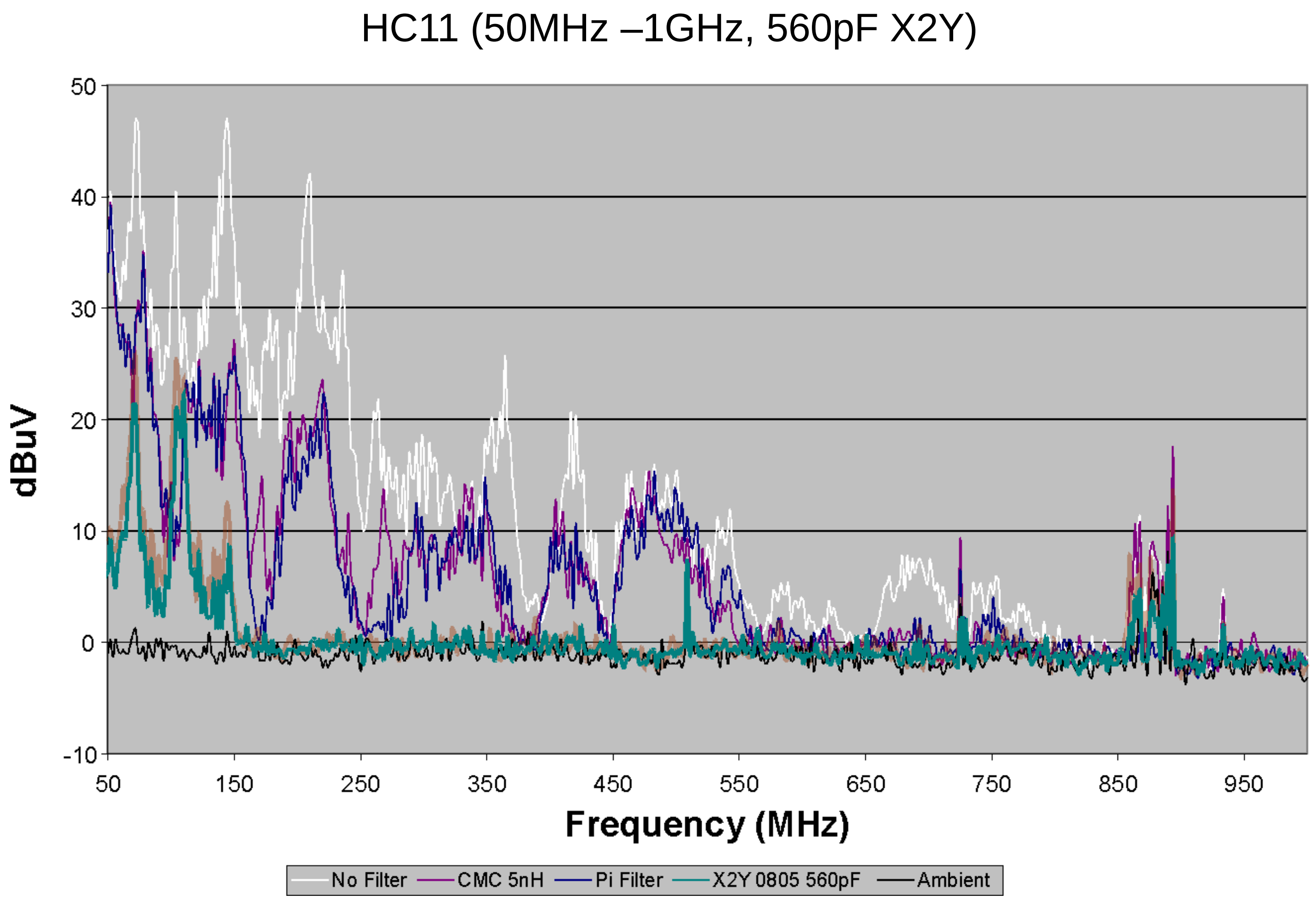
HC11 (50MHz –1GHz, 330pF X2Y)



# Comparative Performance Application

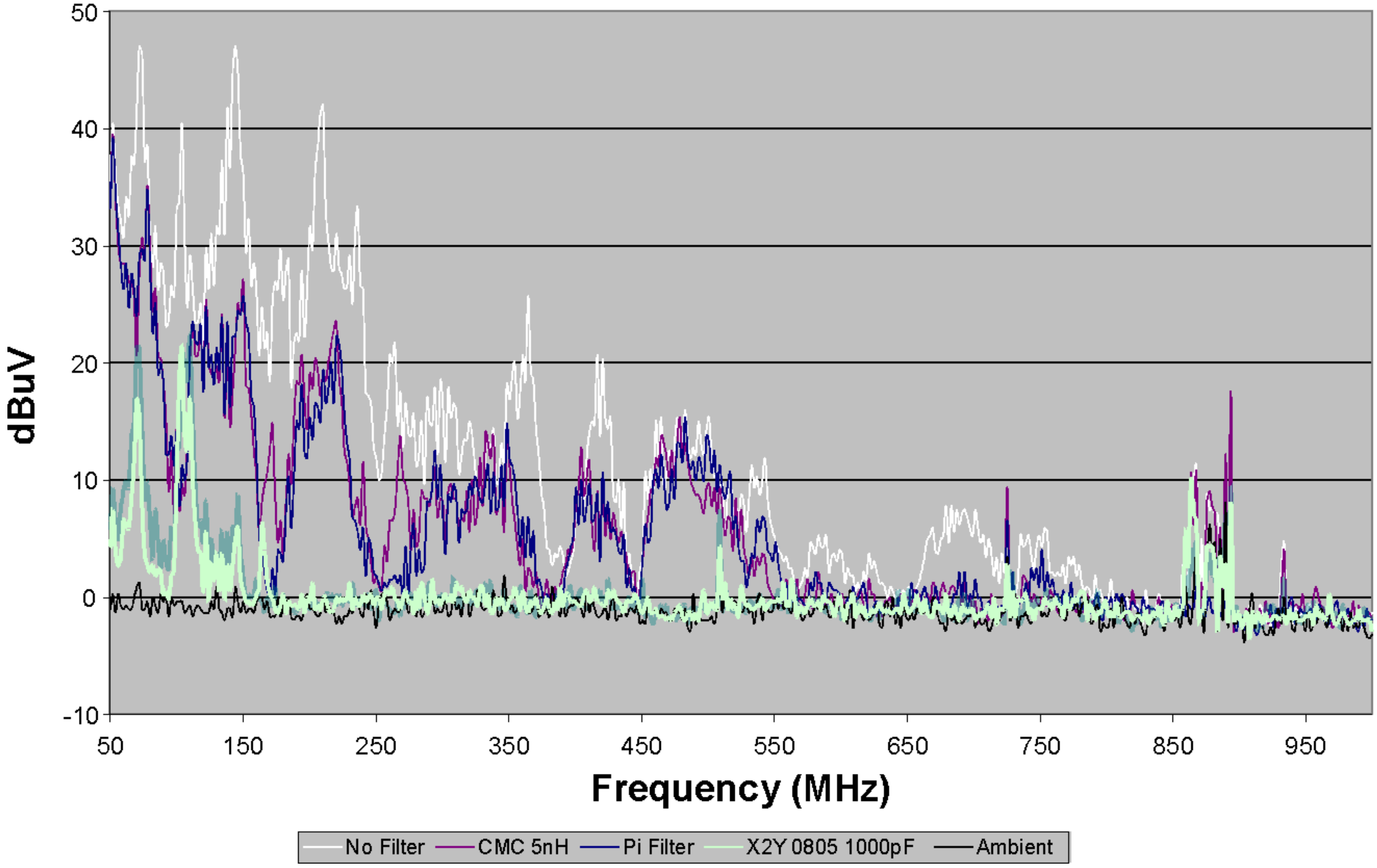


# Comparative Performance Application

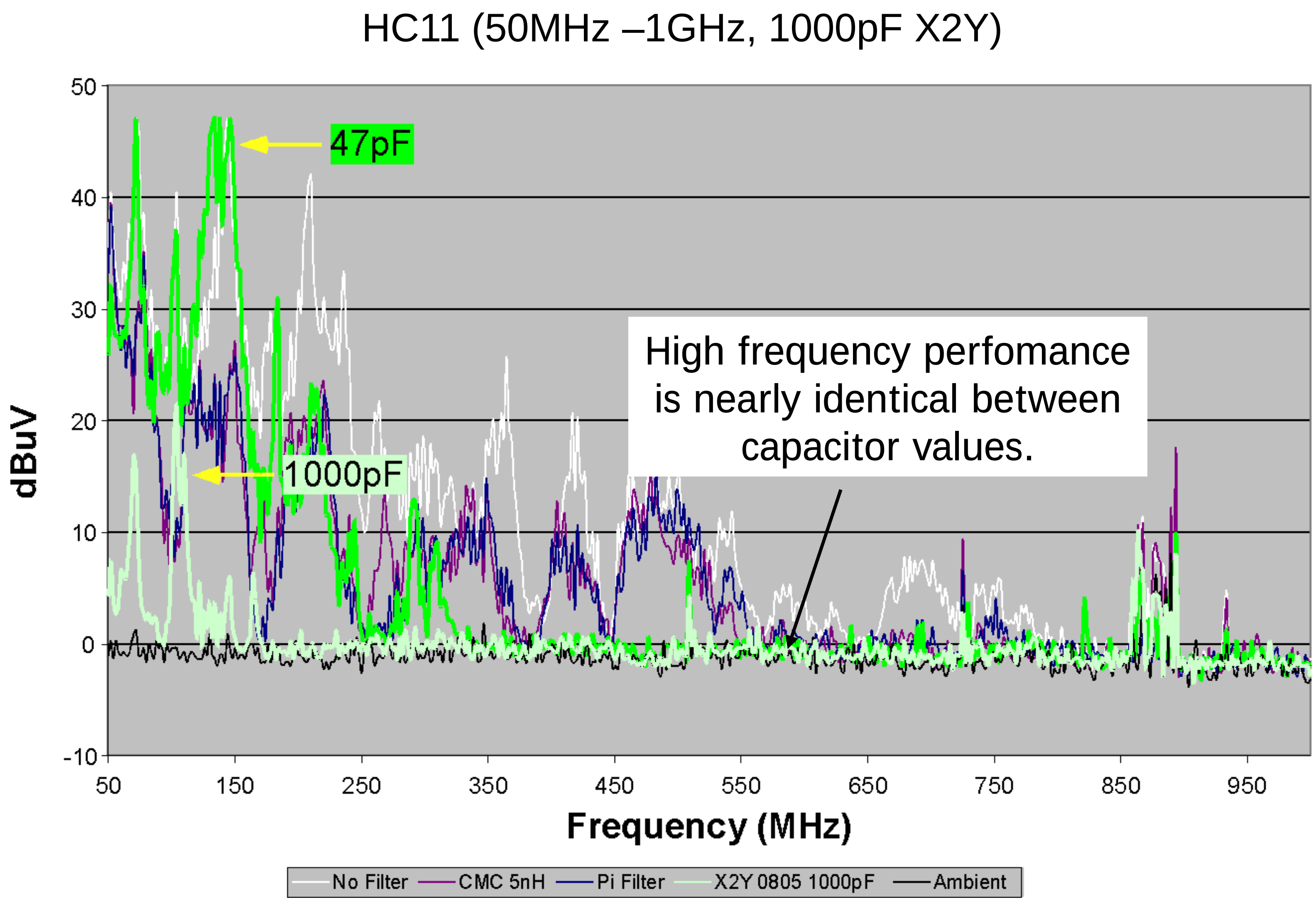


# Comparative Performance Application

HC11 (50MHz –1GHz, 1000pF X2Y)

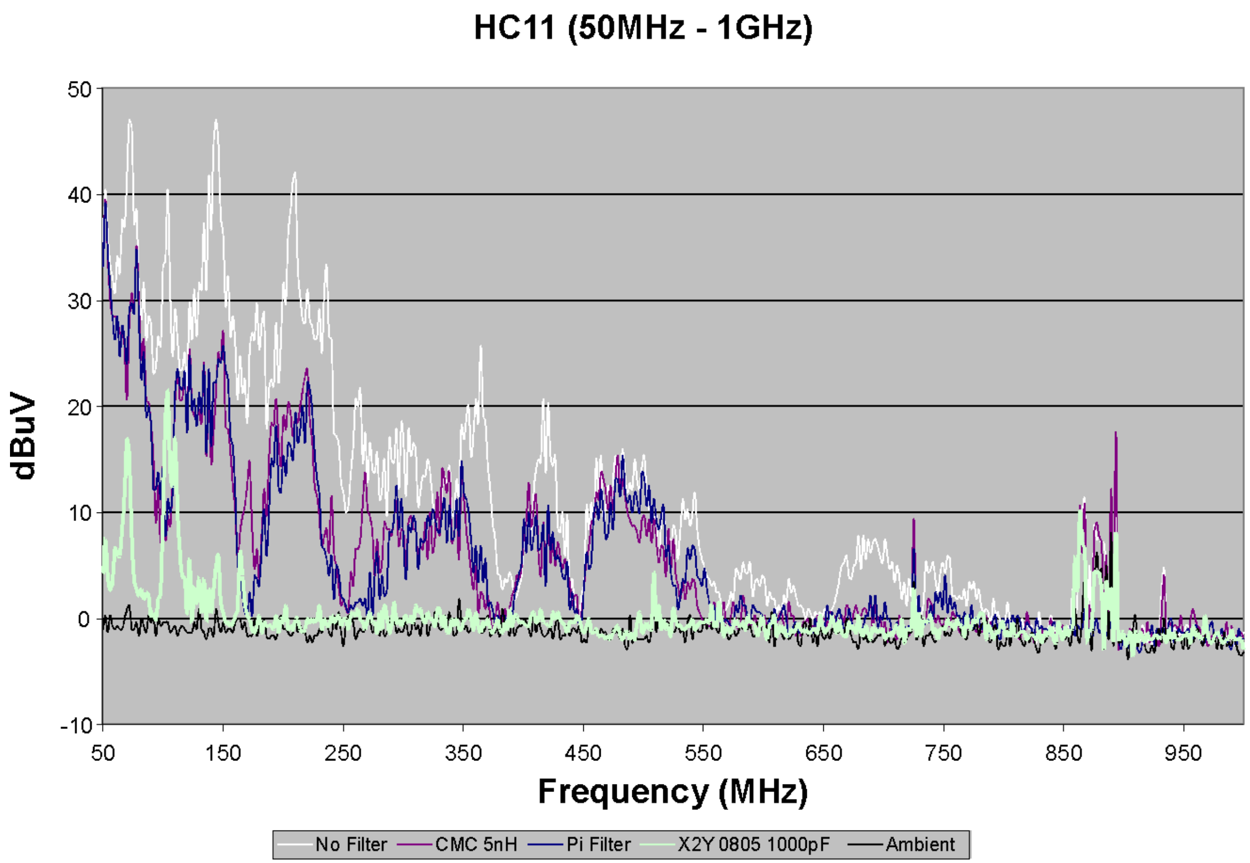


# Comparative Performance Application



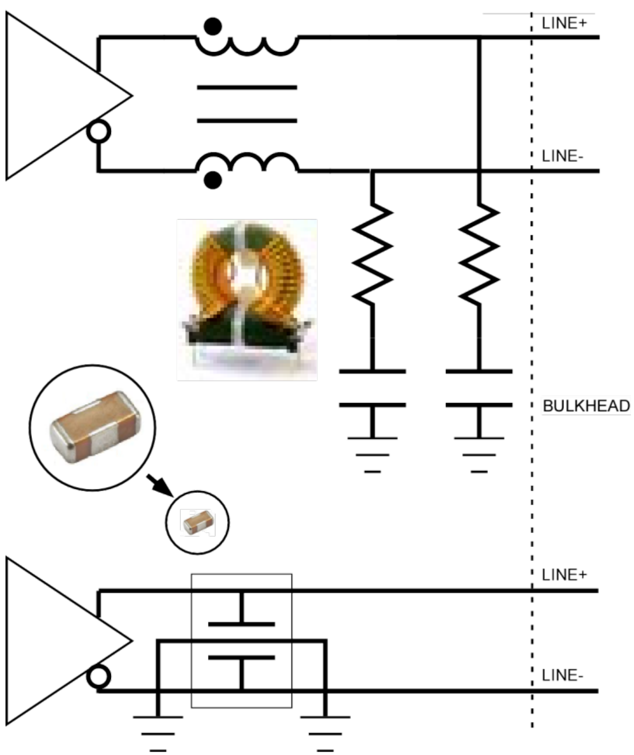
# Comparative Performance Application

- X2Y® 1000pF vastly better radiated emissions than 5uH CM choke or PI filter



# Comparative Performance Application

CLASS D AUDIO DRIVER
CM CHOKE vs X2Y®





In this design, each X2Y 1206 0.1uF capacitor was used to replace a common mode choke, two resistors and two capacitors to achieve the filter results shown above.

# X2Y® Capacitor Selection

- X2Y® capacitors operate as shunts.
  - Attenuate all energy above cut-off frequency
  - Select to pass required signal energy / block offensive HF noise.
  - Use capacitance value that is large enough to attenuate effectively to lowest noise frequency, but no larger than necessary.
- Four recommended selection methods:
  - 1. Pass a required signal rise / fall time.
  - 2. Pass a required signal rise / fall time as a bit interval %.
  - 3. Cut-off HF noise at a specific frequency.
  - 4. Substitute for a specific CM choke.

# X2Y® Capacitor Selection Method 1.

- Use Acceptable Signal Rise and Fall Times
- Establish $T_{RISE}$ / $T_{FALL}$
  - $C <= T_{RISE\_10\%\_90\%\ \_MIN}/(2.2*Z_{SOURCE})$
- Example: CAN BUS 1Mbps, 120 Ohm
  - $T_{RISE\_10\%\_90\%} <= 50ns$
  - $Z_{SOURCE}$ = 120 Ohms / 2 (Loosely coupled diff pair) = 60 Ohms
  - $C_{MAX} <= 50ns/(2.2*60\ Ohms)$
  - $C_{MAX} <= 380pF$
  - Recommended value = 330pF
  - $T_{RISE\_10\%\_90\%} <= 44ns$

# X2Y® Capacitor Selection Method 2.

- Pass Signal Rise and Fall Times Based on Signal Bit Rate and % Allowable $T_R$ / $T_F$
- $T_{RISE\_10\%\_90\%}$ / $T_{FALL\_90\%\_10\%}$ < 5-10% of bit period is usually OK
  - 5%
    - C <= 1/(44*Bit_Frequency*$Z_{SOURCE}$)
    - CAN BUS
      - C <= 1/(44*1MHz*60 Ohms) <= 380pF
  - 10%
    - C <= 1/(22*Freq*$Z_{SOURCE}$)

# X2Y® Capacitor Selection Method 3.

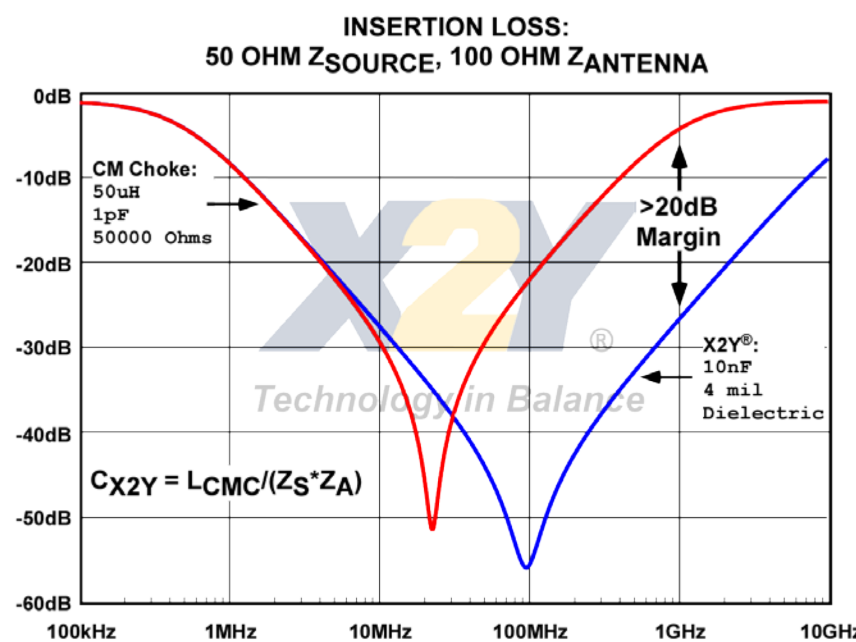
- Cut Noise Down to a Specific Low Frequency
- Noise cut-off frequency $F_{CO}$ is known, source impedance $Z_{SOURCE}$ and antenna impedance $Z_{ANTENNA}$.
  - C => $1/(2\pi * F_{CO} * (Z_{SOURCE} || Z_{ANTENNA})$
- Example: Switching power supply harmonic suppression
  - $F_{CO}$ = 200kHz
  - $Z_{SOURCE}$ = transmission line impedance 10 Ohm
  - $Z_{ANTENNA}$ = 150 Ohm
  - $C_{MIN}$ >= $1/(2\pi*200kHz*10||150$ Ohm) = 1/1.26E7 = 80nF
  - Recommended minimum value = 100nF
- Use larger capacitances for lower frequencies and/or lower impedances.

# X2Y® Capacitor Selection Method 4.

- Substitute for known CM Choke at a known source and antenna impedance:
  - Match choke low frequency insertion loss:
    - $C_{X2Y} >= L_{CM}/(Z_{SOURCE} * Z_{ANTENNA})$
    - $L_{CM}$ is the coupled inductance.
      - Typically ≈ 2X Inductance measured with second winding open
  - If $Z_{SOURCE}$ and/or $Z_{ANTENNA}$ are not known:
    - Assume 50 Ohms for $Z_{SOURCE}$
    - Assume 100 Ohms for $Z_{ANTENNA}$
    - Yields a conservative result that will perform equal or better in a real application

# X2Y® Capacitor Selection Method 4.

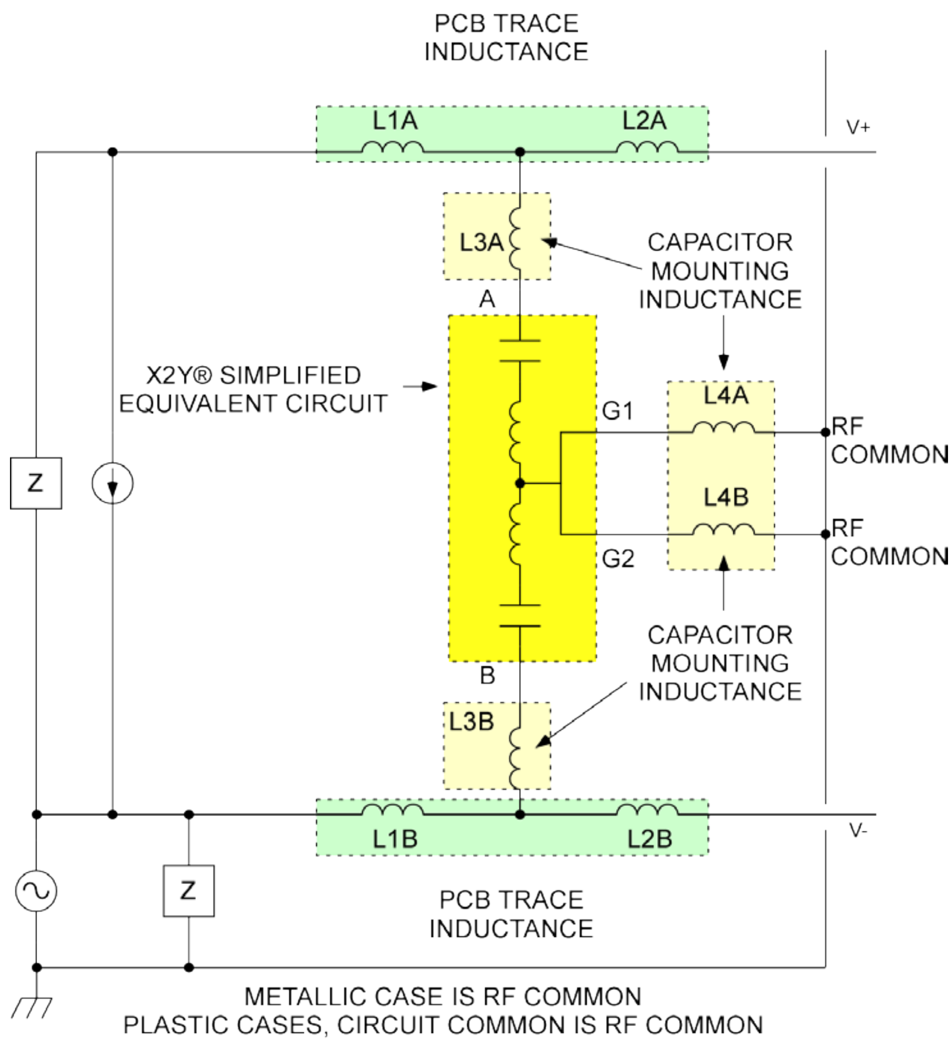
- Example
  - 50Ω $Z_{SOURCE}$
  - 100Ω $Z_{ANTENNA}$
  - 50uH CM Choke
- $C_{X2Y}$ = 50uH/(50Ω*100Ω)
  - 10nF rated value
  - 4 mil dielectric to ground
- X2Y® matches LF performance
- X2Y® provides > 20dB insertion loss improvement @ 1GHz



# X2Y® Capacitors, Best Practices Circuit 1

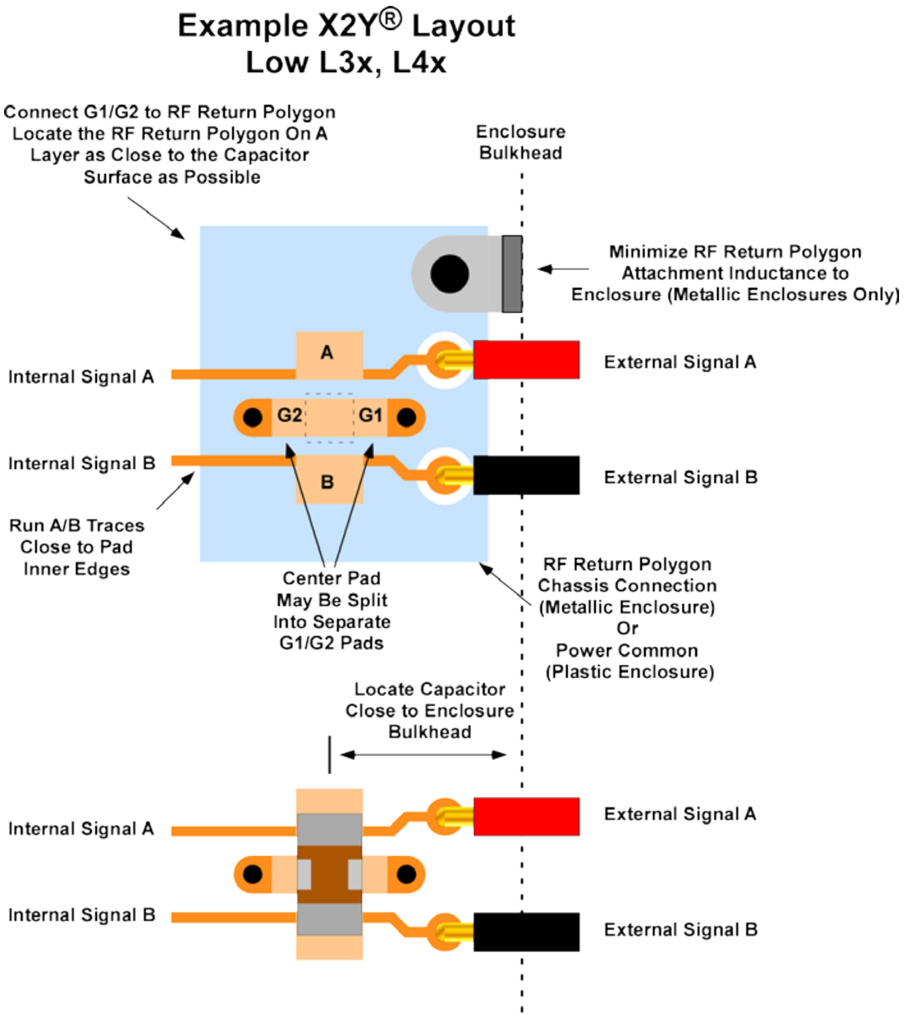
- Performance is typically limited by external capacitor wiring inductance:
  - L3A/L3B, L4A, L4B
- Maximize performance by minimizing L3x, and L4x inductances.
  - Follow X2Y® mounting guidelines.
- L1x, and L2x inductance is OK and even beneficial when balanced.
  - Limitation on L2 is to keep connection close to egress.

X2Y® Circuit 1 CM Filter

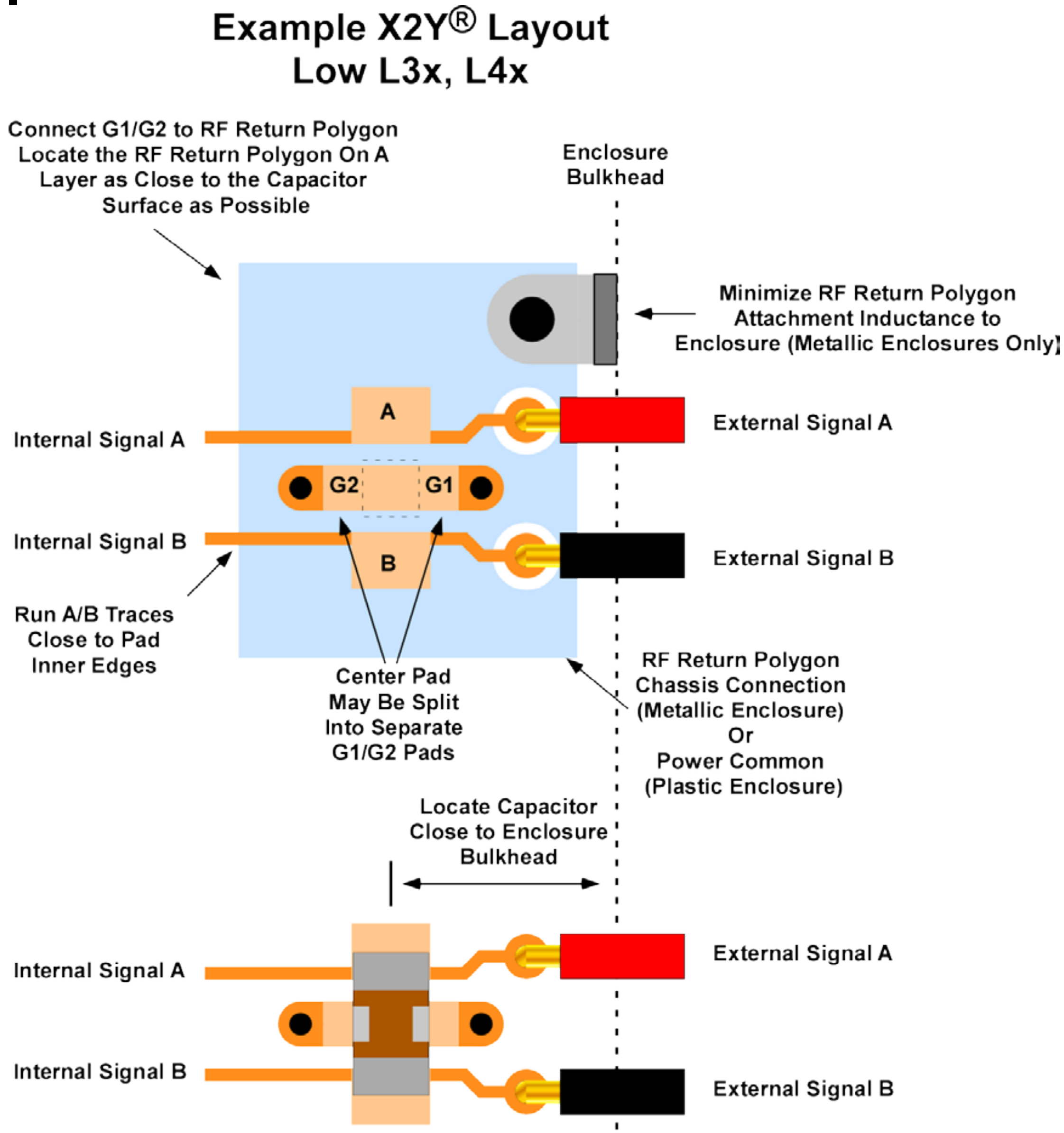


# X2Y® Capacitors, Best Practices Circuit 1

- Locate capacitors close to bulkhead
- Minimize, L3A, L3B
  - Connect A, B pad connections near base of pads
- Minimize L4A, L4B:
  - Connect G1/G2 to RF return polygon on an internal PCB layer as close to the capacitor surface as possible.
    - Chassis for metal enclosures
    - Power common plane for plastic enclosures.
    - 12mil vs 4mil upper dielectric costs about 3dB insertion loss @1GHz
  - Metal enclosures attach RF return polygon to chassis w/ low inductance
    - Multiple attachments along PCB edge recommended



# X2Y® Capacitors, Best Practices Circuit 1

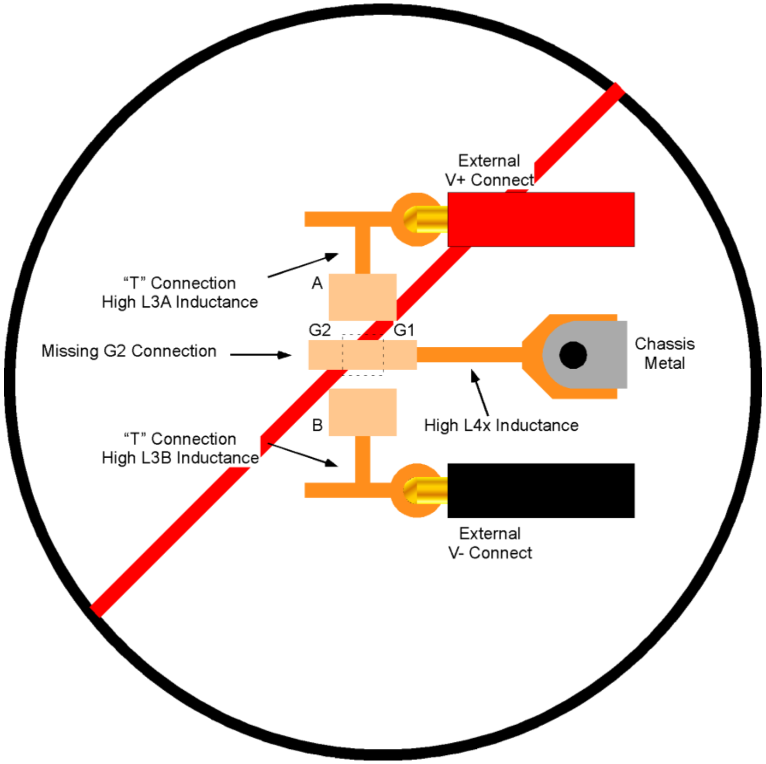


# X2Y® Capacitors, Mounting Errors

Example, Circuit 1 Mount:

- AVOID THESE BAD PRACTICES:
  - "T" to A, or B pad connections
  - Leaving G2 unconnected
  - Stringer trace from any pad.
- Any of the above practices insert substantial inductance which impairs performance at high frequency.




Example X2Y® Layout
Mistakes to Avoid
High L3x, L4x

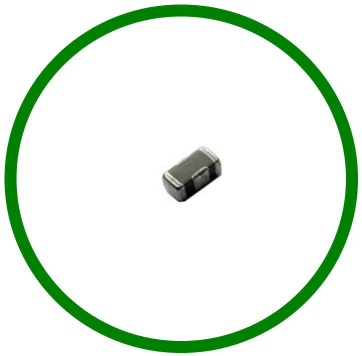
# Summary

- Most EMI problems are Common Mode.
- Reduce common mode by attenuating driving voltage and/or mismatching antenna impedance.
  - Properly mounted X2Y® caps do both
- Series elements suffer from mode conversion and/or poor CM insertion loss at high frequencies.
- X2Y® capacitors maintain good CM insertion loss and mode conversion figures into the GHz.

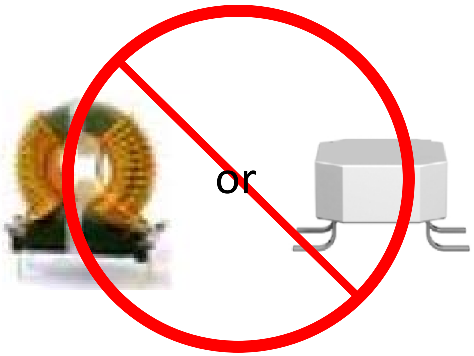
# Summary

- Magnetics noise suppression degrades as actual circuit antenna impedance increases above measuring instrument 50Ω impedance.
  - Real w/150Ω antenna is typically 3dB ***worse*** than 50Ω VNA measurement
- X2Y® noise suppression improves as actual circuit antenna impedance increases above measuring instrument 50Ω impedance.
  - Real w/150Ω antenna is 3dB ***better*** than 50Ω VNA
- X2Y® capacitor values may be easily selected to filter EMI based on any:
  - Required signal pass-band (sets max capacitor value),
  - Required noise stop-band (sets min capacitor value),
  - Improved replacement for existing CM magnetics

# Summary



- X2Y®
  - Small, Light
  - Lower Cost
  - Higher Reliability
  - Lowest Assembly Cost
  - Superior HF Performance




- CM Choke
  - Large, Heavy
  - Expen$ive
  - Subject To Vibration Induced Failure
  - Poor HF Performance