PDN Application of Ferrite Beads

11-TA3

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Objectives

- Understand ferrite beads with a good model
- Understand PDN design w/ sensitive loads
- Understand how to determine when a ferrite bead based filter makes sense and when it does not
- Understand filter synthesis to design req’ts
  - Summarized, details in manuscript

Ferrite Bead Properties

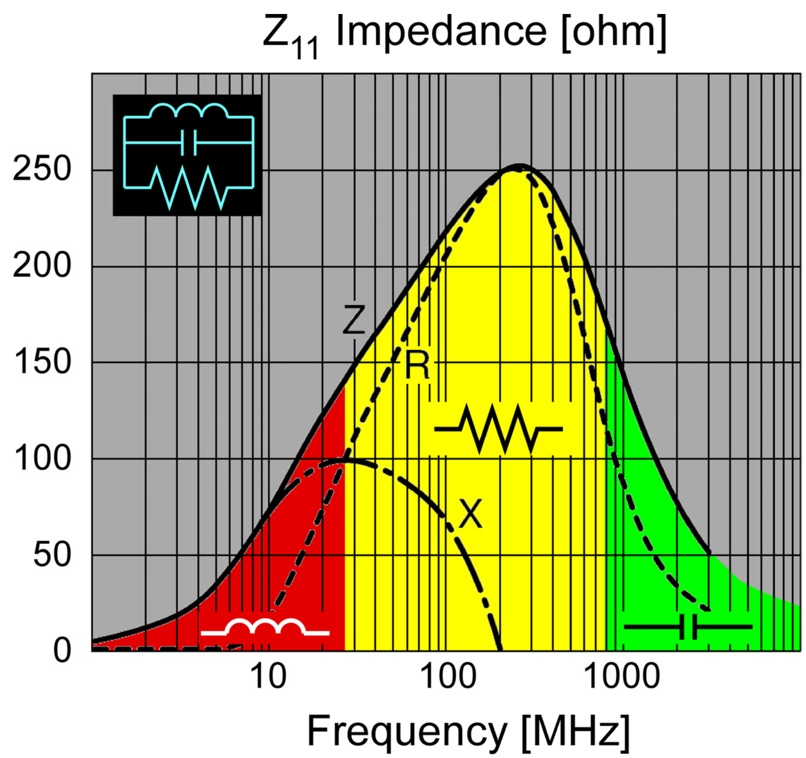
- **<u>Ferrite beads are not magic</u>**.
  - They are neither panaceas, nor or they demons from PDN hell.
- Ferrite beads are components like any others which have very useful properties, but impose side-effects which must be considered.
- Proper applications occur where the benefits outweigh the costs of the side-effects.

Ferrite Bead Properties

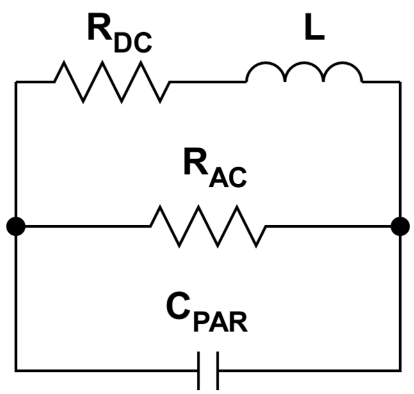
- Sintered compositions
- Two families dominate beads:
  - MnZn
    - Lower frequency power material
    - Lower resistivity
    - Higher permeability
  - NiZn
    - Higher frequency material
    - Higher resistivity
    - Lower permeability

Ferrites Make Excellent Inductors

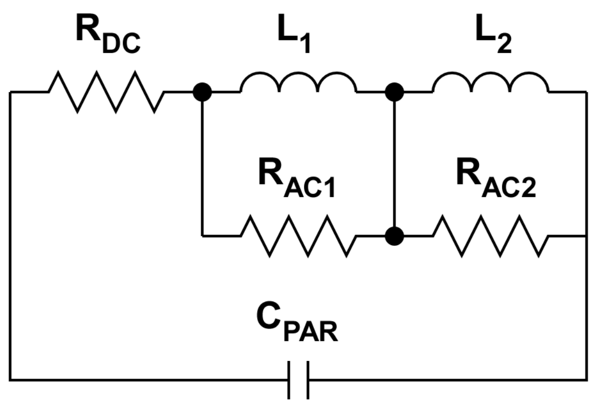
- Beads are typically resistive over 1-2 frequency decades
  - At lower frequencies they are inductive
  - At higher frequencies they are capacitive
- Some NiZn ferrite beads are high Q inductors well past 100MHz.
  - TDK MPZxxxxDyyy beads are inductive to 300-400MHz



Models

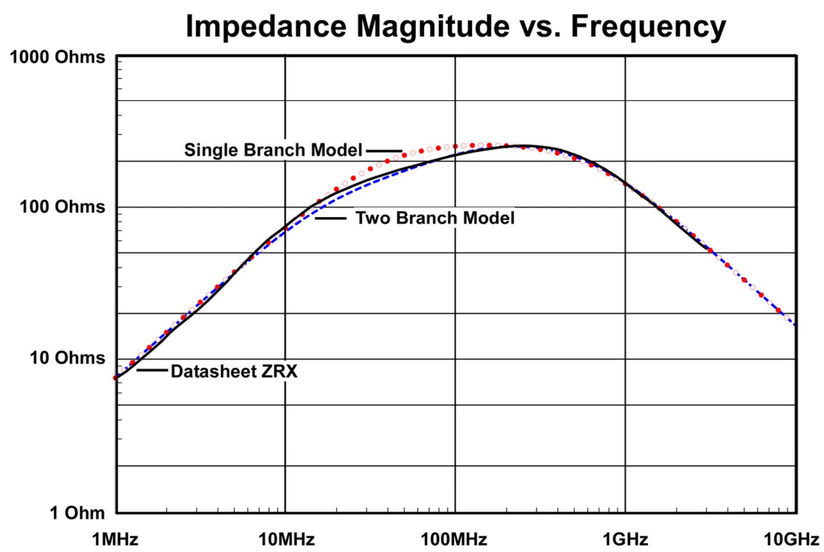


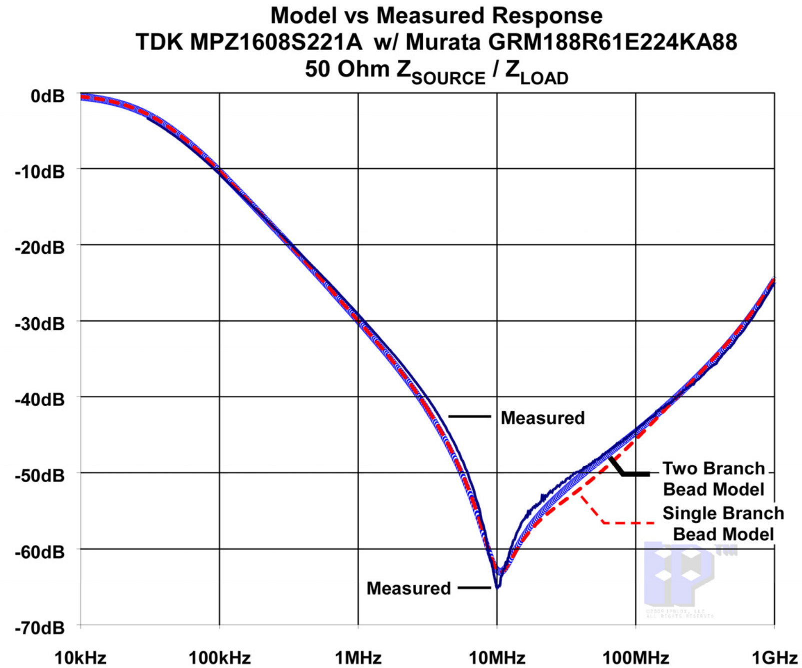
Single-Branch Model



Two-Branch Model

Example Model Fit



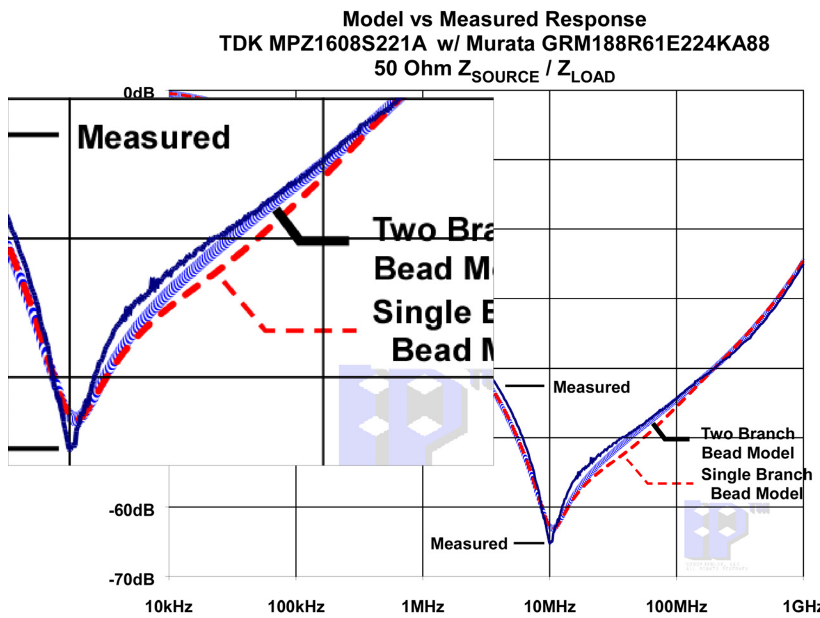


Component Only

Filter Response 50 Ohm Ports

Example Model Fit

- 1 Branch and 2 branch models both closely track actual response with only minor variations deep in the stop band.



Filter Response 50 Ohm Ports

Available Bead Characteristics

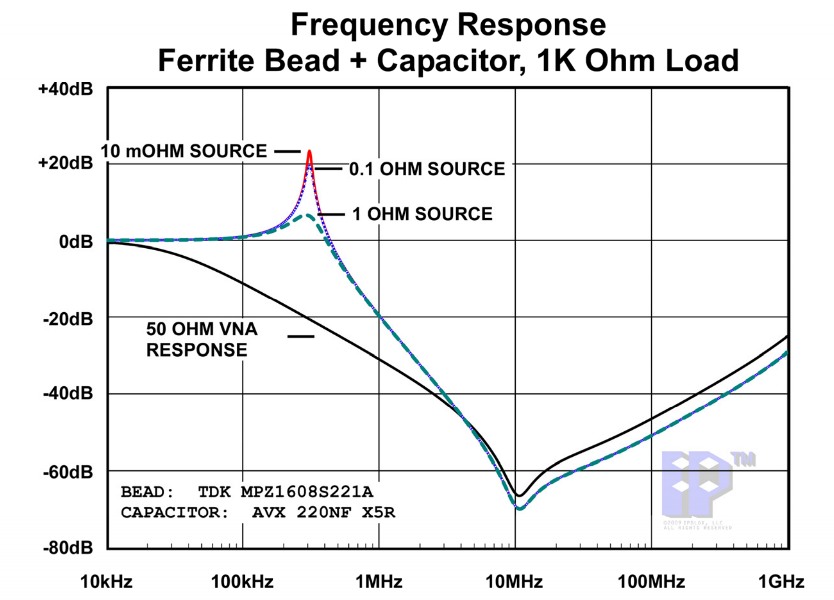
- Beads are available with equivalent inductances from 10's of nH to several uH.
- If lower inductance is needed, consider making an inductor out of a small etch segment:
  - $L \approx \mu 0 * \mu r * H * L/W$
    - H Dielectric height in mils
    - L/W dimensionless length / width

DC BIAS

- Beads are subject to saturation effects
- DC bias above 30-40% of rated current can substantially drop effective inductance by 50% or more.
  - How much depends on how aggressively I_{MAX} has been rated.
  - Simulate with both min and max load currents
  - F_{co} shifts-up at higher biases
  - Q reduces at higher biases
  - Reduces insertion loss
- Beware of some vendor SPICE models for AC analysis
  - Some models have been developed for transient response and have questionable AC response.
  - Best to derive performance from measurements or data sheet ZXR or S params at required bias.

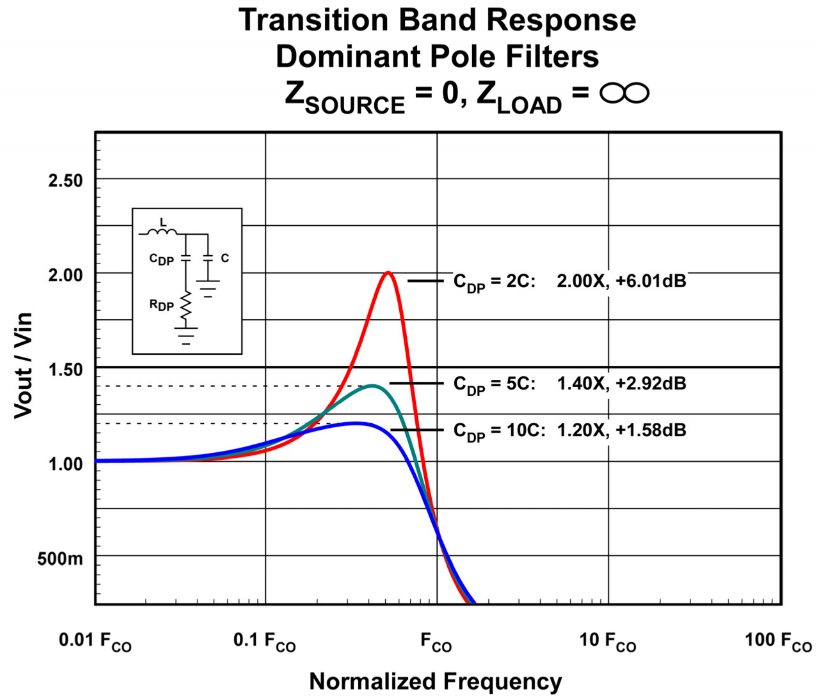
LPF F_{CO} Resonance

- Lightly loaded series LC filters resonate
- Ferrite beads high Q inductor at F_{CO} for most applications
- Lots of noise insertion gain is possible near F_{CO}
- For PLLs this can be very problematic, especially when F_{CO} is located close to a noise source like an SMPS switching frequency.



Damp LC Filters w/Dominant Poles

- Dominant pole advantages:
  - No added DC drop
  - No insertion loss reduction in stop-band
  - No added DC power consumption
- Disadvantages
  - Additional larger capacitor required to form the dominant pole
- C_{DP} = 5C is usually a good design compromise
  - C_{DP}, R_{DP} tables in manuscript

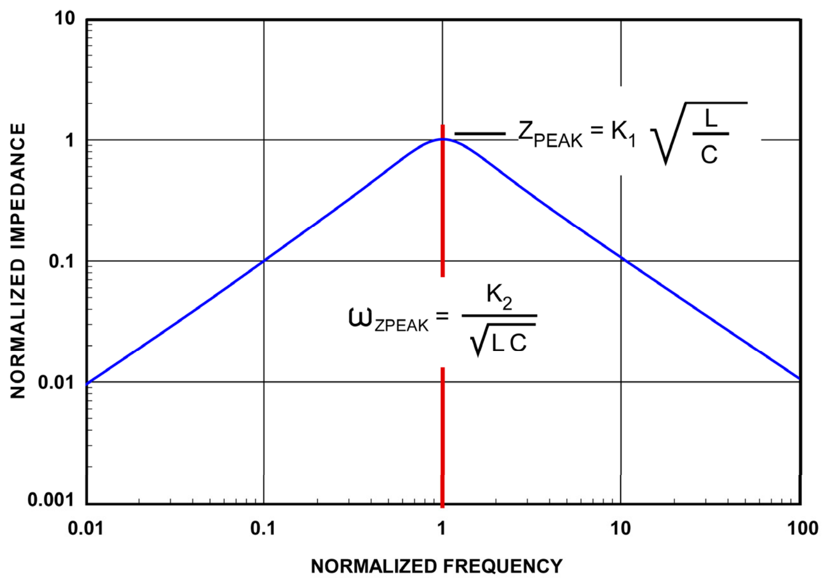


Series Filter Z_{22} Impedance

- Series filter load side shunt impedance builds to a maximum near F_{CO}.
- More inductance =>
  - Lower FCO,
  - More outside noise insertion loss,

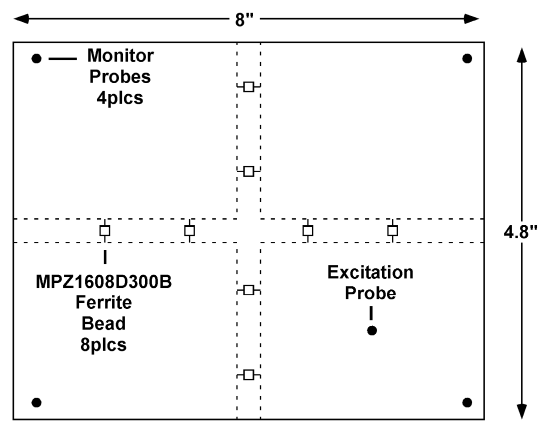
  BUT ALSO

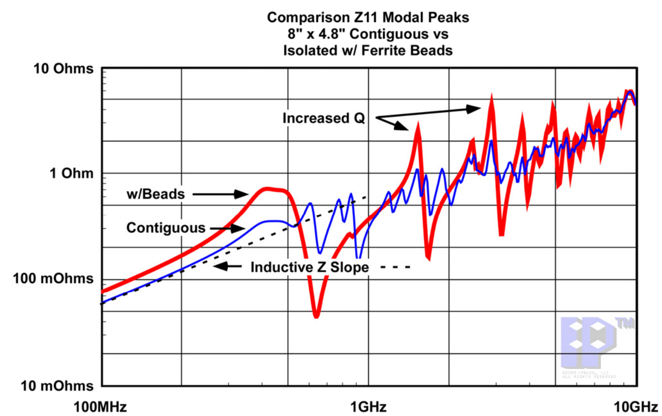
  - **Higher load side impedance**
    - **Load side capacitance must scale w/series inductance to hold a fixed maximum Z_{22}**



Local Plane Isolation w/ Beads

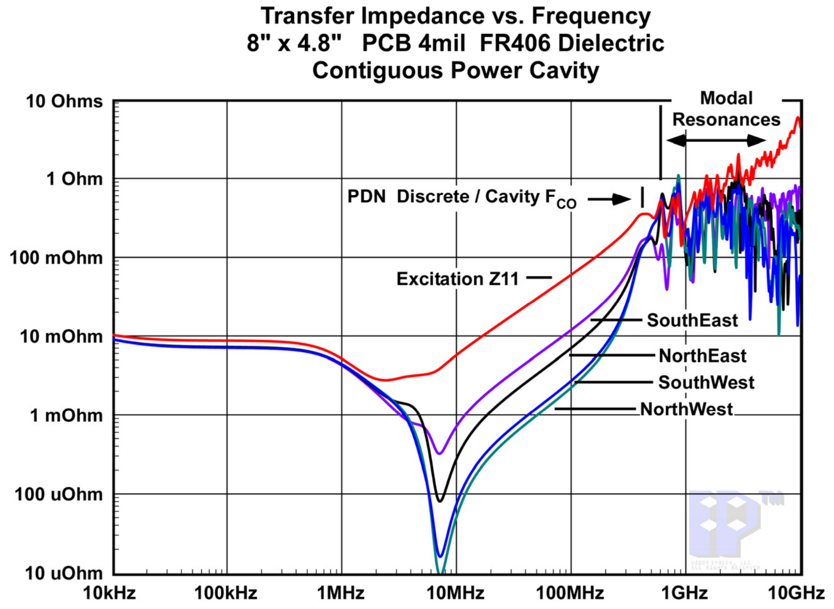
- Contiguous planes versus four quadrants
  - Total is greater than sum of the parts
- Larger plane extents suppress modal resonances:
  - Skin and tangent loss both increase each reflection pass for larger dimensions
  - Smaller polygons:
    - Less loss / pass
    - Higher Q
    - More resonant peaking





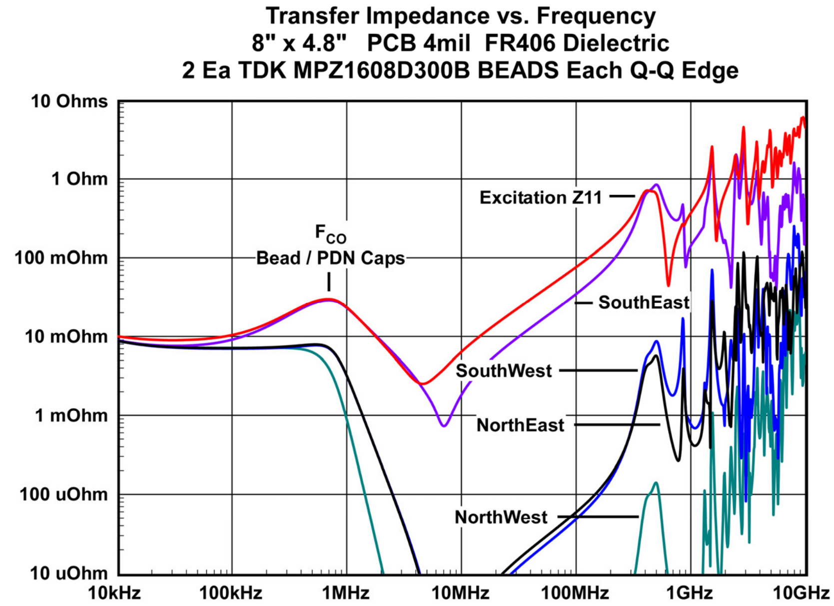
Local Plane Isolation w/ Beads

- Example uniform bypass:
  - 2 ea 1uF 0402 / sq in.
  - 500uF 7mOhm each quadrant
- w/o beads, excited source sees the entire PDN
  - Lower effective Z up to PDN / PCB resonance
  - Little isolation at PDN/PCB resonance and lower modal resonance frequencies



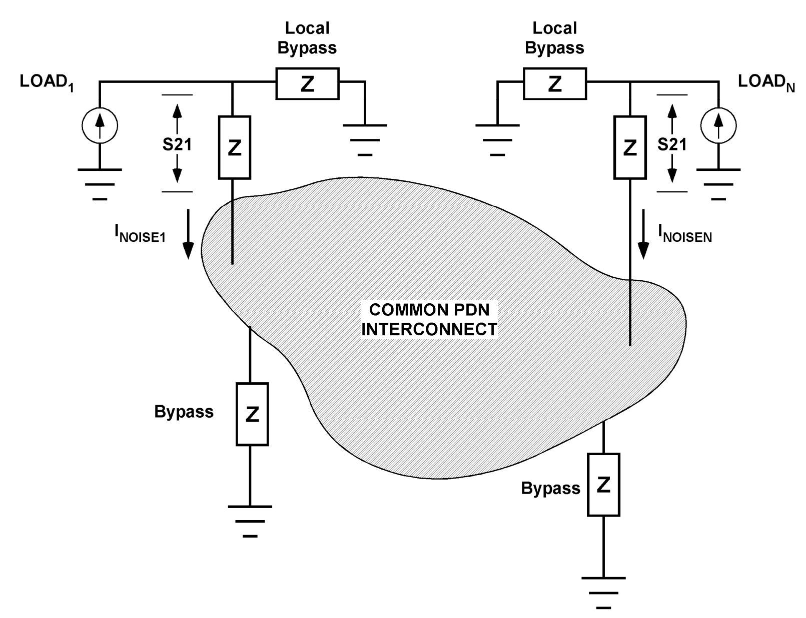
Local Plane Isolation w/ Beads

- w/ beads, excited source sees the entire PDN only up to about ½ F_{CO}.
  - Higher impedance at all higher frequencies than w/o bead.
  - Other quadrants isolate @ FCO and beyond
  - High isolation through PDN resonance, and PCB modal resonances.



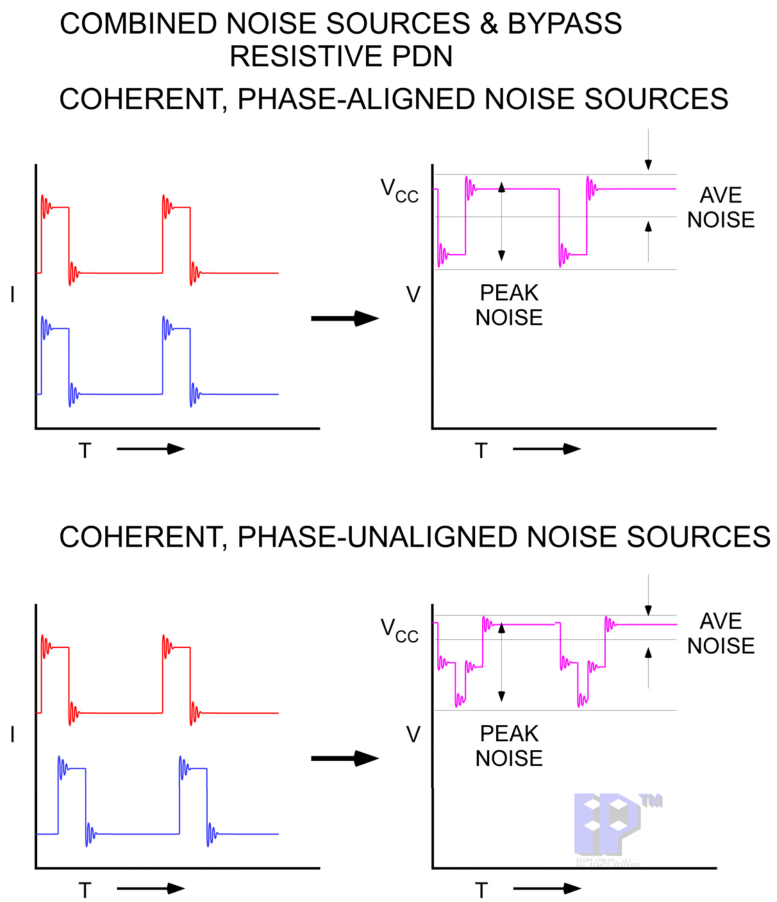
When **Doesn't** Series Isolation Make Sense?

- Loads that tolerate similar noise levels at the common PDN interconnect (planes) do not benefit from isolation.
  - Z_{BYPASS} for each load is inversely proportional to that load's noise current.
  - F.O. approximation bypass is the same joined or isolated.
    - Actually better joined:
      - Noise coherence or lack thereof



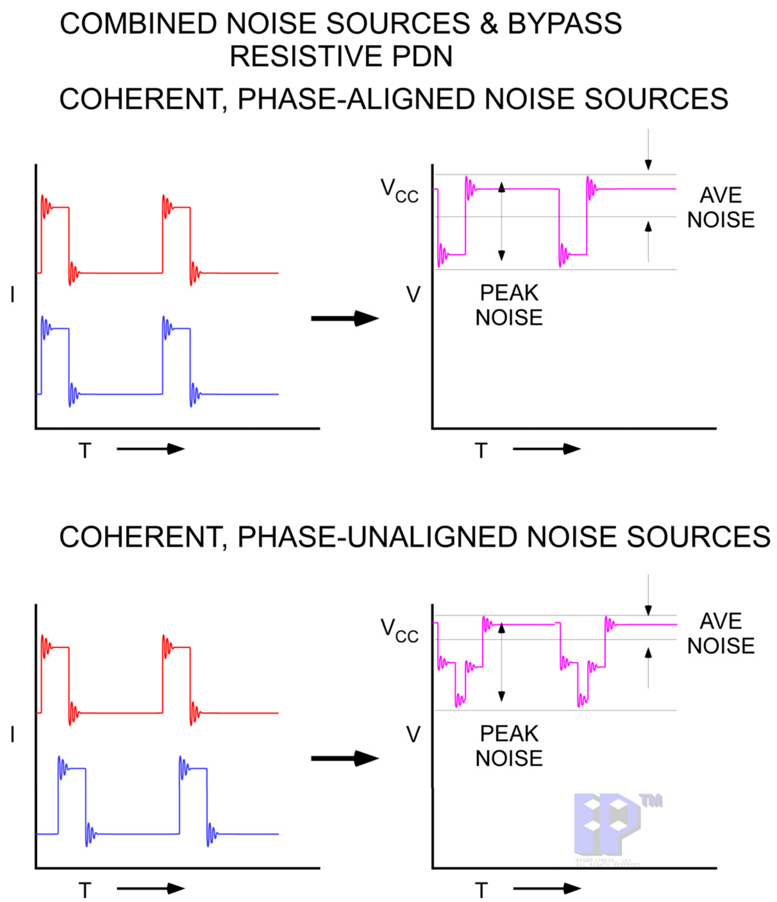
Combined Noise Sources, Equal Noise Tolerance @PCB

- Loads that tolerate similar noise levels at the common PDN interconnect (planes) require bypass admittance proportional to noise current.
- IE constant peak noise voltage.



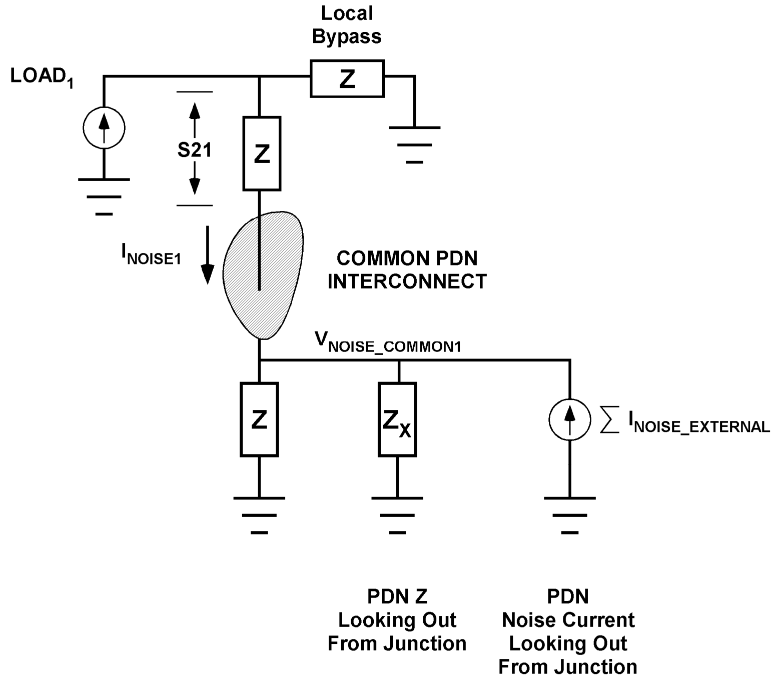
Combined Noise Sources, Equal Noise Tolerance @PCB

- When connected together, the ***PEAK*** noise remains constant
- Average voltage ***ONLY*** remains constant if the noise sources are coherent and in-phase.
- Out of phase reduces ***average*** noise.
- Incoherent drives average noise down by square root of equal sources w/ matched bypass



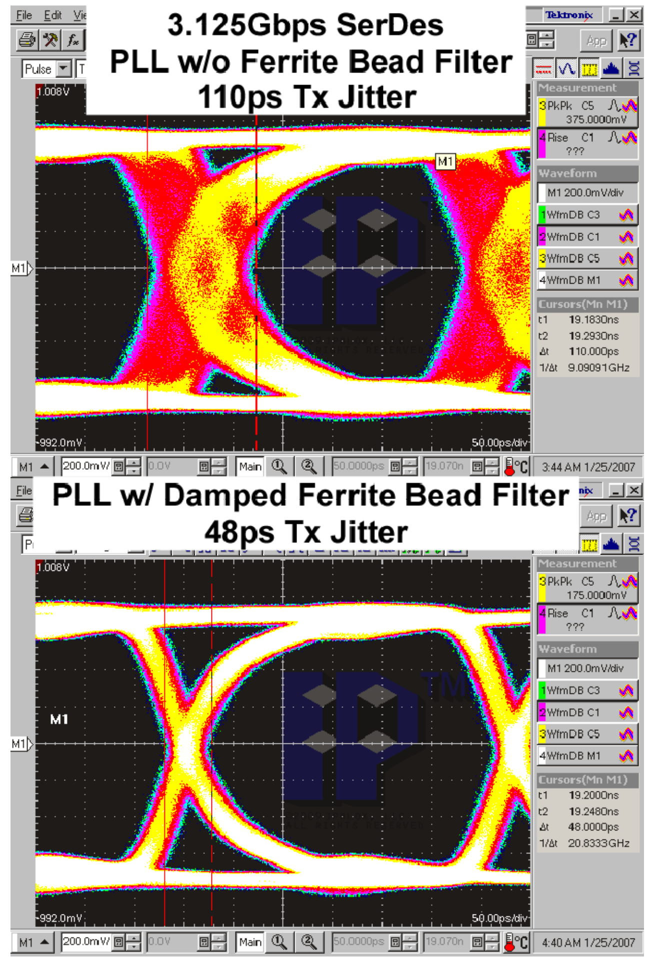
When **Does** Series Isolation Make Sense?

- Loads that do not tolerate similar noise levels at the common PDN interconnect (planes), and where the more sensitive load current does not heavily dominate.
- More tolerant loads are overbypassed to meet sensitive load noise requirements.
- Isolation can result in component reductions of 5:1 or more.



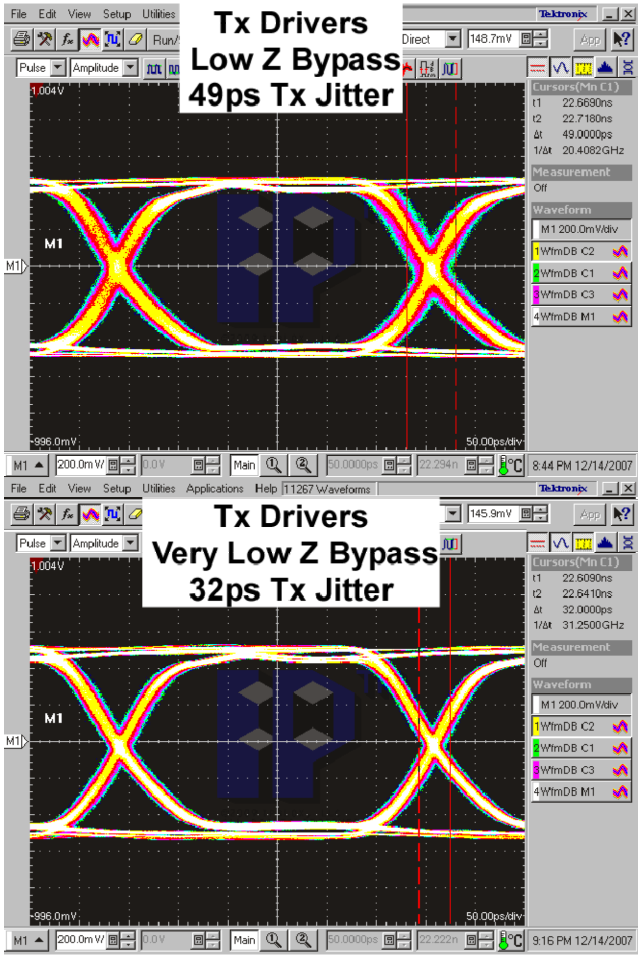
Example PLL Noise Sensitivity

- PLL supply well bypassed in both cases.
- Top:
  - PLL supply common w/digital supply
- Bottom:
  - PLL supply isolated w/ damped ferrite bead filter
- Ferrite bead based series filter is well-justified in this application.



Example Z_{22} Impedance Sensitivity

- Different SerDes than previous example.
- Transmit jitter source is primarily ISI.
- Top:
  - Low impedance PCB AVCCH supply
- Bottom:
  - Improved very low impedance PCB AVCCH supply
- Ferrite beads would aggravate ISI by raising Z_{22}
- **Don't starve high-speed circuits!**



PDN Example, Bead Evaluation

- Analog load: High speed ADC
  - +/-2mV V_{cc} noise tolerance
  - +/-100mA dynamic current
  - 20mOhms Z_{MAX}
- N 1.2V Digital I/Os:
  - +/-30mV V_{cc} noise tolerance
  - +/-N*10mA dynamic current
  - @ +/-2mV Z_{MAX} = 0.2 Ohms/N
  - @ +/-30mV Z_{MAX} = 3.0 Ohms/N

Example

- FOM
  - # of bypass caps required = K/FOM
- Common rail
  - 10 I/Os 20mOhms digital, 20mOhms analog
    - FOM = (.02 || .02) = .010
  - 100 I/Os 2mOhms digital
    - FOM = (.02 || .002) = .0018
- Isolated rails
  - 10 I/Os 20mOhms analog, 300mOhms digital
    - FOM = (.02 || 0.30) = .019
    - .019/0.010 ≈ **1.9:1 component reduction by isolation**
  - 100 I/Os 20mOhms analog, 30mOhms digital
    - FOM = (.02 || .03) = .012
    - .012/0.0018 ≈ **6.7:1 component reduction by isolation**

Filter Synthesis Summary

- Full synthesis procedure detailed in manuscript
- Step #1:
  - **Determine the design requirements:**
    - How much noise does the analog node tolerate vs frequency at the PCB attachment?
      - Translate to insertion loss
    - What is the current vs. frequency from the analog node?
- Without requirements:
  - **Do Not Pass Go, Do Not Collect $200.**

Filter Synthesis Summary

- Choose the lowest inductance bead that will do the job
- Load side capacitance determined by the greater req't:
  - Bead inductance and Z_{22} low frequency impedance requirements
  - Bead inductance and F_{co} requirements.
- Dominant pole damping req'd/not req'd determined by bead L / bypass C Q near F_{co}
  - See manuscript for details
- Load side HF capacitor count determined by Z_{22} vs. high frequency requirements.

Summary

- Ferrite beads are not magic.
- Ferrite beads can be modeled relatively simply for modest DC current swings.
  - Multiple sim passes required if the load has wide DC swing
- Ferrite beads are high Q inductors up to some frequency that depends on the bead material.
  - Some beads are high Q inductors to 100's of MHz
  - More typical is 10MHz – 30MHz
  - Series filter design must account for damping req'ts at F_{co}.
    - Dominant pole is usually the best damping technique when req'd.

Summary Cont'd

- Make PDN no more complex than actually needed.
  - Series filters / partitioning can realize very high noise isolation from low to high frequencies.
  - Series filters and rail partitioning **aggravate**:
    - Signal return routing
    - Layout
    - Noise averaging
    - PCB modal resonances
  - Larger polygons / planes serving more properly bypassed loads yield the lowest average noise levels for a given PDN bypass component count.

Summary Cont'd

- The need for a series filter can only be determined when power delivery requirements are **known**.
- Series filters make sense **only when**:
  - Noise voltage sensitivity at the planes is disparate **AND**
  - The less sensitive loads dominate noise currents
- Always design series filters for the minimum required insertion loss / inductance to do the job.
  - Sometimes a small etch inductor will do better than a bead due to available small inductances.
- **KNOW YOUR POWER DELIVERY REQUIREMENTS!**

Thank You

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