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

• **Ferrite beads are not magic.**
  – 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 MPZxxxxDyyyy 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:
  – \( L \approx \mu_0 \times \mu_r \times H \times L/W \)
  • 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 $I_{\text{MAX}}$ has been rated.
  – Simulate with both min and max load currents
  – $F_{\text{co}}$ 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 $F_{CO}$,
  - 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 $\frac{1}{2} F_{CO}$.
  - 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.
  - $Z_{\text{BYPASS}}$ 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 = \( (.02 | | 0.30) = .019 \)
    • \( .019/0.010 \approx 1.9:1 \) component reduction by isolation
  – 100 I/Os 20mOhms analog, 30mOhms digital
    • FOM = \( (.02 | | .03) = .012 \)
    • \( .012/0.0018 \approx 6.7:1 \) 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:
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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