Advanced materials and design for board level EMI shielding

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February 15, 2012
Outline

• Principle of board level shielding (BLS)
  • BLS shielding principle and materials selection guideline
  • EMI shielding effectiveness testing methods

• Conventional BLS design and materials
  • Metals
    • Mechanical forming
    • Casting
    • Electroforming
  • Form-in-Place (FIP) and Mold-in-Place (MIP)
  • Molded plastics with metallic coating or painting

• Emerging BLS materials and future trends
  • Conductive hybrid composites
  • Absorbing materials
  • Nano-composites

• Conclusions
Basic principle of board level shielding

- Based on Faraday cage principle, BLS can be designed with different forms, depending on the application requirements and mounting methods.

*Typical 5 sided metal can is used to form 6 sided shield through the attachment/connection to the ground plane on PCB*
• **Major functions of BLS**

  • Shield different zones of a device from each other
  • Cover it – no inside EMI escape, and no outside EMI entering
  • Ground/seal it – no EMI leakage
  • Manage system heat dissipation
  • Minimize real estate used
  • Minimize weight and cost

• **Key factors for effective shielding**

  **MATERIAL**
  • Electrical conductivity/permeability/permittivity
  • Wall thickness/surface coating
  • Thermal conductivity
  • Environmental compatibility
  • Manufacturability

  **Geometry**
  • Holes
  • Slots
  • Gaps

  **Termination**
  • Shield-Board interface
  • Connectivity
  • Joining/Mounting methods

**Cost usually dominates material selection for BLS**
• EMI shielding materials are designed to harness, capture, and ground the EMI energy

• Absorbing materials are designed to attenuate and absorb electromagnetic energy, and convert it into heat

**WAVELENGTH AND FREQUENCY RELATIONSHIP**

\[ \text{Wavelength [mm]} = \frac{300}{f \text{ [GHz]}} \]

1GHz has a wavelength of 300 mm

**Common EMI Shielding Range**

<table>
<thead>
<tr>
<th>Power</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Radio waves</td>
</tr>
<tr>
<td>FM</td>
<td>Microwaves</td>
</tr>
<tr>
<td>VHF</td>
<td></td>
</tr>
<tr>
<td>UHF</td>
<td></td>
</tr>
</tbody>
</table>

**Frequency (Hz)**

- 1
- 10
- 100
- 1000
- 10000

**Wavelength [m]**

- 100
- 10
- 1
- 0.1
- 0.01

**Different materials are usually suitable to different frequency ranges. Composites with hybrid structures can be future universal shielding materials**
- EMI shielding principle of conductive materials

Reflection loss depends on the distance of the EMI source to the material (different for electric, magnetic, and plane waves), material electrical conductivity, and the frequency of the incident wave.

\[ SE = R + A + B \]

\[ R_E = 321.8 + 10 \log \left( \frac{\sigma}{f r^2 \mu} \right) \]

\[ R_H = 14.6 + 10 \log \left( \frac{f r^2 \sigma}{\mu} \right) \]

\[ R_P = 168 - 10 \log \left( \frac{f \mu}{\sigma} \right) \]

Where \( R_E, R_H, \) and \( R_P \) are the reflection losses for the electric, magnetic, and plane wave fields expressed in dB; \( \sigma \) is the relative conductivity referred to copper; \( f \) is the frequency in Hz; \( \mu \) is the relative permeability referred to free space; \( r \) is the distance from the source to the shielding in m.
• Absorption Loss

\[ E_1 = E_0 e^{-t/\delta}, \text{ and } H_1 = H_0 e^{-t/\delta}. \] The distance required for the wave to be attenuated to 1/e or 37% is defined as the skin depth, \( \delta \).

\[ \delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \]

\[ A = 20 \ln \left( \frac{t}{\delta} \right) = 131 \ t \sqrt{f \mu \sigma} \]

Where \( A \) is the absorption or penetration loss expressed in dB; \( t \) is the thickness of the shield in mm; \( f \) is frequency in MHz; \( \mu \) is relative permeability (1 to copper); \( \sigma \) is conductivity relative to copper in %IACS.

Absorption loss depends on material thickness, permeability, electrical conductivity, and the frequency of the incident wave. It is the same for all electromagnetic waves.
• Effect of Apertures on Shielding effectiveness

Electromagnetic fields

Honeycomb waveguide

SE (dB) = 20 log (fc/f) + 27.3 h/d -10log n

where n= total number of cells, and f is frequency and not more than fc/10.

For a round hole
SE_{dB} \approx 102 -20 \log (df_{MH}) + 30 \left(\frac{t}{d}\right) \mid d<\lambda/2

Number n ventilation holes (if s < \lambda/2, d > \lambda/2, and s/d <1)
SE (dB) \approx 20 \log (\lambda/2d) -10 \log n

For a regular shaped slot
SE_{dB} \approx 100 -20 \log( w f_{MH} ) + 20\log[1+\ln(w/h)] + 30 \left(\frac{t}{w}\right) \mid w<\lambda/2

where w is length of slot and w>h and w>>t; \lambda is wavelength in meter; f_{MH} is frequency in MHz.
• Example: Calculated shielding effectiveness difference with different corners

The longest dimension of the aperture limits or dominates the BLS shielding effectiveness.
• EMI shielding effectiveness testing methods

MIL-STD-285 – Shelters - Withdrawn
NSA 65-6 and 73-2A – Shelter SE measurements
MIL-DTL-83528 – Conductive Elastomer EMI Gasket Radiated Field and DC Volume Resistivity
IEEE STD 299 – Shelters (replaced MIL-STD-285)
IEEE STD 1302 – Guide to EMI Gasket Test Methods
ASTM D4935 – Planar Materials - Withdrawn
ASTM E1851 – Shelters (duplicates MIL-STD-285)
SAE ARP 1705 – EMI Gasket Transfer Impedance
SAE ARP 1173 – EMI Gasket Radiated Field
EN 50147-1/VDE 0876-147-3 – Enclosure SE Measurement
IEC 61000-5-7 – Enclosures Degree of Protection
IEC 61000-4-21 – Reverberation Chamber Test Techniques
SCTE 48-1-2006 – GTEM Cell Tests

EMSCAN
• EMSCAN functionality and configuration

- Spectral scans
  - Problem frequencies
- Real-time spatial scans
  - Sources of radiated emissions
- 50 kHz to 4 GHz
- Constant or intermittent emission sources
- Compare function
- Overlay function
- PCB design overlay
  - Gerber or FPGL
- Automated report generator
• EMSCAN example 1 – Absorbing material
• EMSCAN example 2 – Waveguide
## Conventional BLS design and materials

<table>
<thead>
<tr>
<th>Shielding Type</th>
<th>Mount/installation</th>
<th>Features</th>
<th>Shielding effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal cans</td>
<td>Soldered over PCB</td>
<td>Pick and place assembly</td>
<td>40 - 100 dB</td>
</tr>
<tr>
<td></td>
<td>with surface mount</td>
<td>with reflow process</td>
<td></td>
</tr>
<tr>
<td></td>
<td>technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductive plastic</td>
<td>Pin, screw or snap-on</td>
<td>Mold to shape, with surface plating or conductive painting</td>
<td>30 - 100 dB</td>
</tr>
<tr>
<td>covers</td>
<td>mount over PCB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form-in-place</td>
<td>Robotic dispensing</td>
<td>Crosstalk and perimeter shielding</td>
<td>70-120 dB</td>
</tr>
<tr>
<td></td>
<td>on thin-walled BLS/enclosures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mold-in-place</td>
<td>Conductive elastomer</td>
<td>Component shielding and grounding</td>
<td>70 - 120 dB</td>
</tr>
<tr>
<td></td>
<td>molded over frames of BLS/enclosures</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Proper selection of BLS systems depends on the balance of performance, reliability and cost.
• Metals

• Mechanical forming
  - Bending, stamping or drawing
  - Tin plated CRS, SS, Al, or Cu alloys
  - Nickel silver

• Cast Al, Mg or Zn

• Electroforming

Mechanically formed metal cans are the low cost and most common used BLS especially with high volume production.
• CRS with composite coatings

  • Tin whisker can be a concern for tin plated CRS BLS

  • Mitigation practices include thicker tin coating, nickel underplate, annealing, and alternative coatings, etc.

  • To alleviate the tin whisker growth concern and provide relatively low cost BLS, Chromate-free electrogalvanized steel (ZE-38) and ECO-TRIO steel, have emerged as promising BLS shielding materials.

Special resin film designed for
• oxidation-protection coating
• good solderability
• Relatively high surface conductivity
• Not subject to whiskers
• Die casting for BLS/Enclosures

• Major advantages
  - Durable, robust enclosure solution
  - Match with environmental sealing (space gaskets, including FIP, MIP etc.)
  - Good for thermal dissipation

• Disadvantages
  - Heaviest BLS/enclosure (minimum thickness 0.4 mm)
  - Draft requirement means sloped sidewalls
  - Die tooling cost is a major concern for small scale production

• Die casting materials typically include Al, Mg, and Zn
  - Al has good corrosion resistance and mechanical properties, high thermal and electrical conductivity, and strength at elevated temperatures
  - Zn is the easiest alloy to cast because of its low melting point, which is economical for production of small BLS parts
  - Mg is the lightest alloy in common use
• **Electroforming**

  • Electroforming is a special fabrication method for BLS products with requirements for very small, very thin, very fine or very precise dimensions and patterns.

  • Handling design complexity is a further key strength of electroforming. By growing components in nickel or other metals on a mandrel, features and tolerances can be managed automatically. Minute components and complex features that cannot be achieved by any other manufacturing method may be produced by Electroforming.

  • A wide variety of shapes and sizes can be made by electroforming, but the principal limitations are (a) shaping of mandrel; and (b) being the need to separate the part from the mandrel.
• **Form-in-Place (FIP)**

  • FIP is a robotically controlled dispensing process to apply conductive shielding gaskets on BLS, enclosures, covers and components, which offer cost savings in the form of reduced raw materials, labor, and assembly time.

  • FIP gaskets are typically comprised of a foamed, gelled, or unfoamed elastomer resin, used as carrier for conductive fillers. The dispensability of the material can be the major limitation for the FIP process. Typical size of FIP ranges from 0.38 to 2.3 mm high and 0.38 to 3.1 mm wide.

  • Can be cured by heating or at room temperature with good adhesion on a wide variety of metal or plastic substrates

  • Provide high shielding effectiveness: 70-100dB to 18GHz
- **Mold-in-Place (MIP)**
  - MIP technology uses unique molding process to create small and complex electrically-conductive elastomer gaskets on the frame of metal or plastic BLS, or on the substrate of PCB
  - Replaces multiple shield cans with a single piece approach
  - Ideal for hand held devices where space is at a premium
  - Metal component can be custom designed in various shapes, mounting tabs, and heights
  - Elastomer mold-in-place ribs can be provided with a tapered design to lower compression force
• Molded plastics with metallic coating or painting
  • Offer light weight and improved performance over metal cans in some applications

Pros:
  • Light weight
  • Provide more aesthetic options
  • less corrosion risk
  • Generally best for small and portable designs

Cons:
  • Generally less durable than metal BLS
  • Poor thermal dissipation
  • Generally the EMI shielding performance depends on surface coating or plating
  • Scratches can be slots so handling can be critical to shielding performance
  • Lack of recyclability of coated plastics and the potential environmental impact of spray coating/plating
• Typical conductive coating on plastic BLS

<table>
<thead>
<tr>
<th>Conductive Coatings</th>
<th>Thickness</th>
<th>Shielding Effectiveness (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 GHz</td>
</tr>
<tr>
<td>All-over Copper/Nickel Plating</td>
<td>1.0 - 1.25 µm</td>
<td>120</td>
</tr>
<tr>
<td>Selective Copper/Nickel Plating</td>
<td>2.0 - 2.5 µm</td>
<td>71</td>
</tr>
<tr>
<td>Copper Loaded Paint</td>
<td>0.025 mm</td>
<td>70</td>
</tr>
<tr>
<td>Copper-Silver Hybrid Paint</td>
<td>0.025 mm</td>
<td>69</td>
</tr>
<tr>
<td>Silver Loaded Paint</td>
<td>0.0125 mm</td>
<td>62</td>
</tr>
<tr>
<td>Copper/Stainless Steel Vapor Deposition</td>
<td>0.5 µm</td>
<td>48</td>
</tr>
<tr>
<td>Aluminum Vapor Deposition</td>
<td>0.5 µm</td>
<td>46</td>
</tr>
</tbody>
</table>

All-over plating offers the best shielding effectiveness and the lowest cost. Vapor deposition can offer relatively low cost although some degree of shielding effectiveness may be sacrificed. Conductive paints can provide high shielding effectiveness with relatively high cost depending on the constituents.
Emerging BLS materials and future trends

- Conductive hybrid composites
  - Metal fiber/whisker reinforced composites
  - Nonmetallic fiber/whisker reinforced composites
  - Flexible composite film

- Absorbing materials
  - Electromagnetic absorbers
  - Dielectric absorbers

- Nano-composites
  - Carbon-nanotube reinforced composites
  - Graphene transparent BLS
  - Electrospinning nanofiber composites
• **Conductive hybrid composites**
  - Optimal selection of reinforcements and base materials to get best compatibility;
  - Optimizing the layout of the reinforcements to maximize the percolation effect

• **Metal fiber/whisker reinforced composites**

  - **Reinforcement or filler**
    - Al, Cu, Fe, S.S., Ag, Ti, Co, Ni, Ti, W etc.

  - **Matrix**
    - Selected polymer
    - Hydrogen-rich polymer
    - Rare-earth-doped rubber

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Stainless steel fiber/whisker reinforced composite
• Nonmetallic fiber/whisker reinforced composites

• Reinforcement or filler
  - Metal coated or Intercalated graphite fiber or foam; boron fiber; Nanotube or nanofiber etc.

• Matrix
  - Selected polymer
  - Hydrogen-rich polymer

Ni plated carbon fiber with dispersion agent
• Flexible composite film

• Ideal for thinning and weight saving of electronic devices in communication industry
• Absorbing materials

• Material absorption capability in an electromagnetic field

\[ A \left( \frac{W}{m^3} \right) = \frac{1}{2} \sigma E^2 + \pi f \varepsilon_0 \varepsilon_R E^2 + \pi f \mu_0 \mu_R H^2 \]

E(V/m) is electric field strength; H(A/m) is magnetic field strength; \( \sigma \) (S/m) is conductivity; \( f \) is frequency; \( \varepsilon_0 \) (F/m) is permittivity of the vacuum; \( \varepsilon_R \) is complex permittivity; \( \mu_0 \) [A/m] is permeability of the vacuum; \( \mu_R \) is complex permeability.

• Absorption of EMI energy rely on the conductivity, dielectric loss and/or magnetic loss of the absorber material

• Dielectric loss is characterized as the complex permittivity (created by carbon or other electrically conductive or capacitive particles) and acts on the electric field

  Dielectric absorbing materials

• Magnetic loss is characterized as the complex permeability (magnetic fillers - special irons and ferrites) and acts on the magnetic field

  Magnetic absorbing materials
• Examples of magnetic absorbers
• Example of some developing absorbers

• Far-infrared radiation absorbing Dallenbach like-structure

• Submilimeter-wave anechoic structure

• Hybrid structure
• Nano-composite materials

• Carbon-nanotubes possess much lower percolation threshold and saturation surface resistivity
• Graphene transparent BLS
  • Exceptional in-plane electrical conductivity (up to ~ 20,000 S/cm)
  • Highest thermal conductivity, ~ 5,300 W/(m-K)

Nano-graphene platelet with a thickness of 0.3 – 100 nm

• Electrospinning nanofiber composites

![Electrospinning Process Diagram]
Conclusions

• BLS can be the most cost-efficient means of solving EMI issues. Materials selection, geometry design, and termination technology are three key factors on the shielding performance.

• Tin plated CRS is the most common BLS material due mainly to its excellent mechanical formability, high permeability, environmental compliance, and relative low cost. The potential tin whisker growth can be mitigated.

• To alleviate the tin whisker growth concern and provide relatively low cost board-level shielding products, some environmentally friendly composite plating steels, have emerged as promising board-level shielding materials.

• Different materials are usually suitable to different frequency ranges. Composites with hybrid structures can be future universal shielding materials.

• Nano-materials would play an important role for future BLS applications.
Thank You!