ILLINOIS
Electrical & Computer Engineering
GRAINGER COLLEGE OF ENGINEERING

Shielding

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Clayton Paul, Introduction to EMC, Chapter 10.

Outline

- Introduction and shielding effectiveness
- Shielding effectiveness: far field sources
- Shielding effectiveness: near field sources
- Low frequency, magnetic field shielding
- Effects of apertures

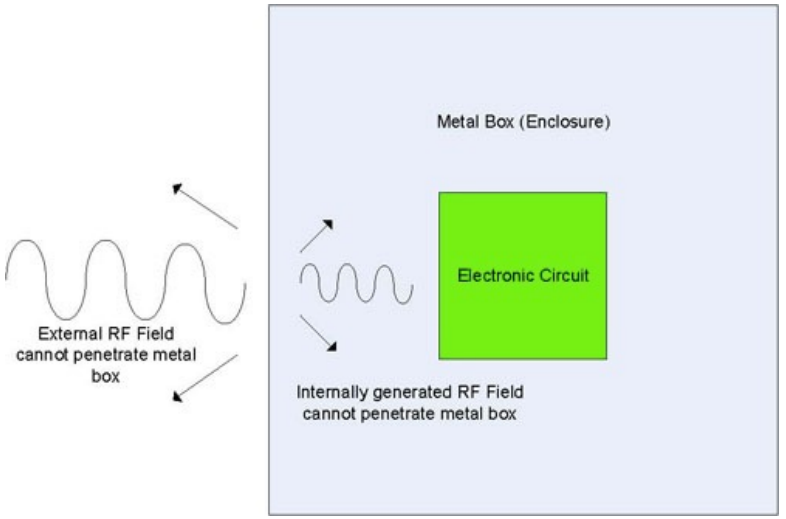
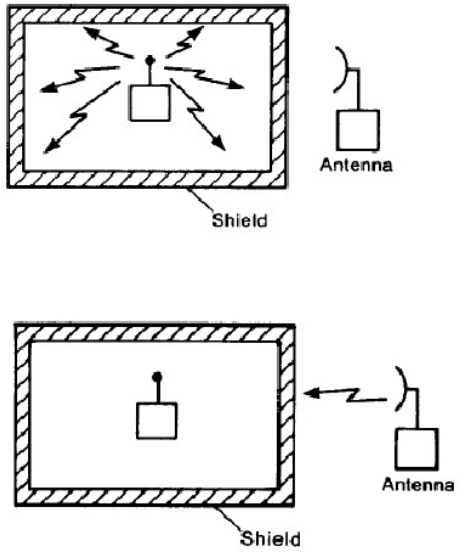


Illustration of the use of a shielded enclosure

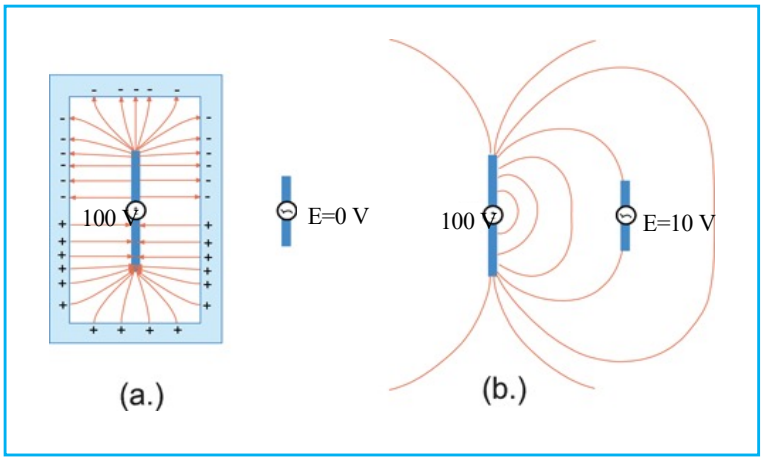
1 Shielding

Shield - usually is a metallic enclosure that completely encloses an electronic product.

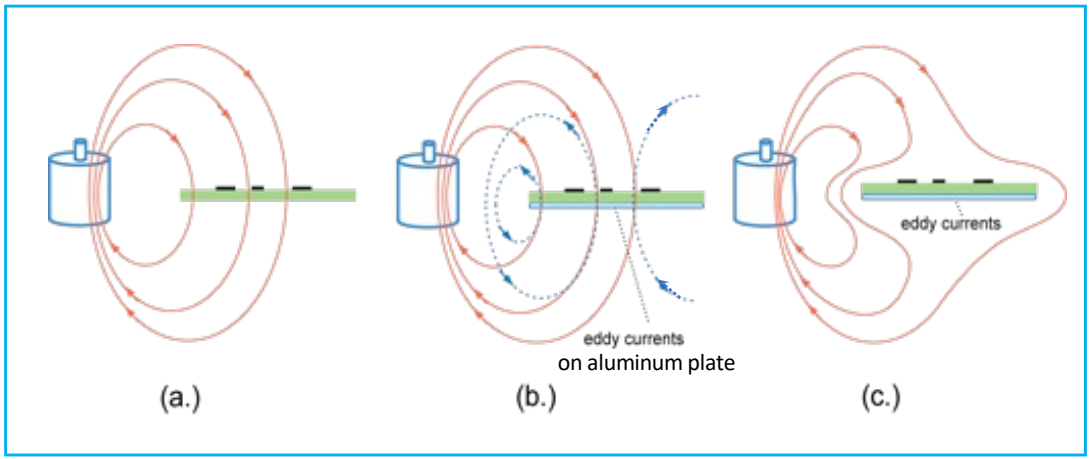
- Purposes of a shield
  - ✓ To prevent the emissions from the electronics radiating outside the boundaries of the product.
    - prevent those emissions from causing the product to fail to comply with the radiated emissions limits
    - prevent the product from causing interference with other electronic products.
  - ✓ To prevent radiated emissions external to the product from interfering the product.



Electric/Magnetic Field Shielding



Electric Field Coupling/Shielding.



Magnetic field shielding with good conductors.

Electric field shielding examples



Before

After

(a.)



Before

After

(b.)

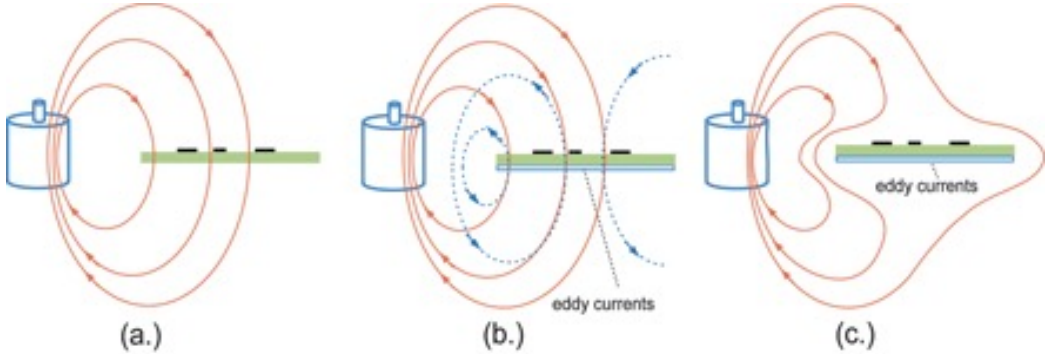


Before

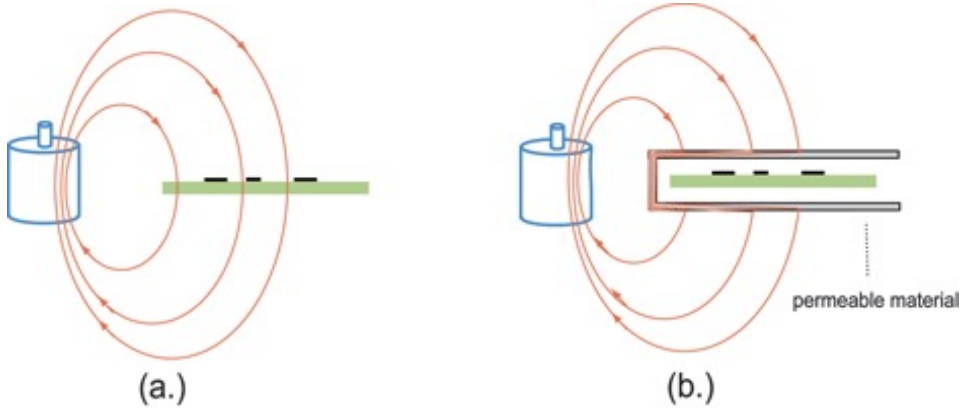
After

(c.)

Magnetic field shielding examples



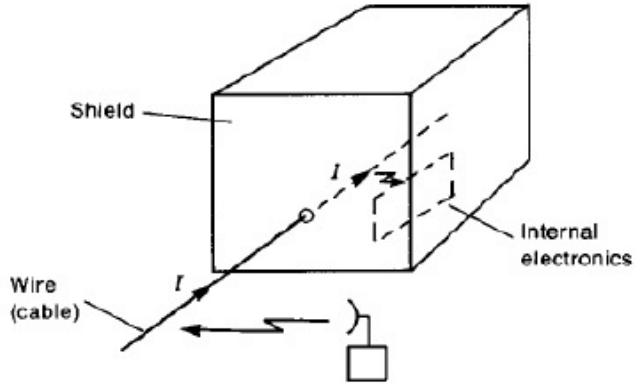
Magnetic field shielding with good conductors



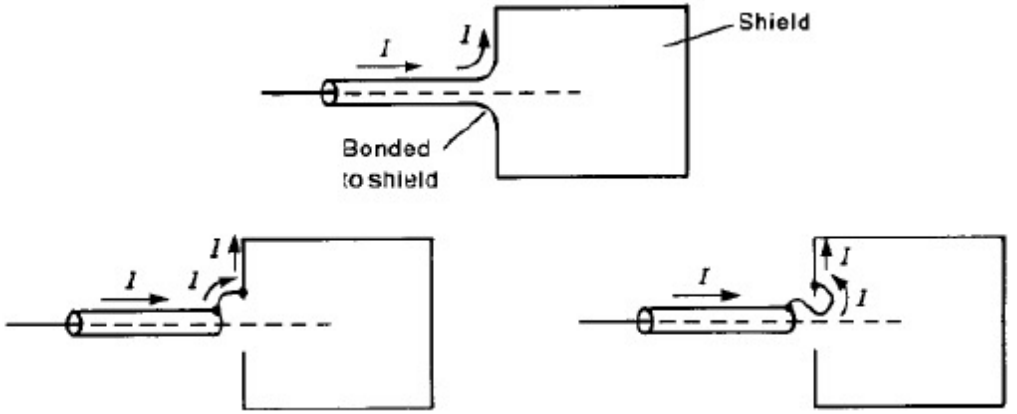
Magnetic field shielding with magnetic materials

Shielding

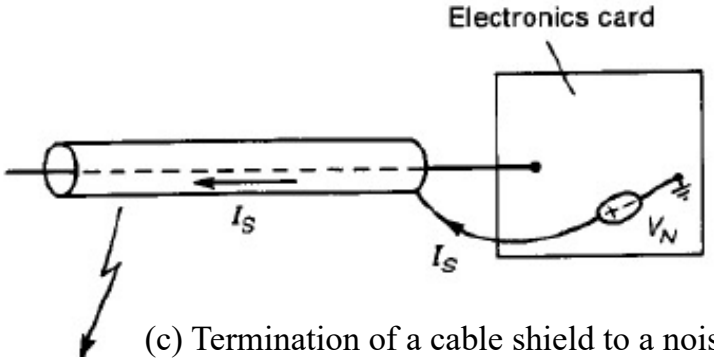
Important practical considerations that seriously degrade shielding effectiveness



(a) Penetration of an enclosure by a cable allowing direct entry (or exit) of external (internal) fields



(b) Pigtail termination of a cable shield at the entry point to a shielded enclosure

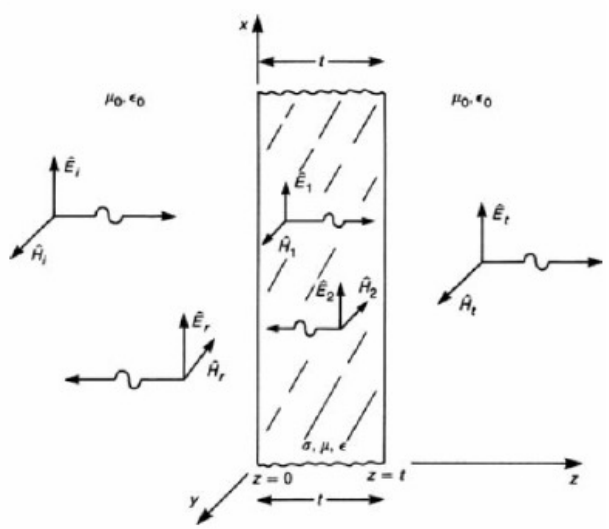


(c) Termination of a cable shield to a noisy point, causing the shield to radiate

Shielding Effectiveness

Illustration of the shielding effectiveness of a conducting barrier to a uniform plane wave

A conducting shield of thickness *t*, conductivity σ, permittivity $\varepsilon=\varepsilon_0$, and permeability μ has an incident uniform plane wave incident on its leftmost surface.



$$\mathrm{SE} = 20\log_{10}\left|\frac{\hat{E}_i}{\hat{E}_t}\right|$$

$$\mathrm{SE} = 20\log_{10}\left|\frac{\hat{H}_i}{\hat{H}_t}\right|$$

Q: Do they be equal ?

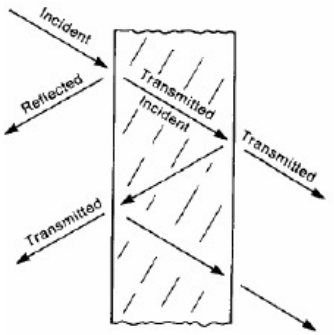


Illustration of multiple reflections within a shield.

Shielding effectiveness =
reflection loss + absorption loss + multiple reflections

$$\mathrm{SE}_{\mathrm{dB}} = R_{\mathrm{dB}} + A_{\mathrm{dB}} + M_{\mathrm{dB}}$$

2 Shielding Effectiveness : Far-Field Sources

Incident wave	Reflected wave			Transmitted wave
$\vec{\hat{E}}_i = \hat{E}_i e^{-j\beta_0 z}\vec{a}_x$	$\vec{\hat{E}}_r = \hat{E}_r e^{j\beta_0 z}\vec{a}_x$	$\vec{\hat{E}}_1 = \hat{E}_1 e^{-\hat{\gamma} z}\vec{a}_x$	$\vec{\hat{E}}_2 = \hat{E}_2 e^{\hat{\gamma} z}\vec{a}_x$	$\vec{\hat{E}}_t = \hat{E}_t e^{-j\beta_0 z}\vec{a}_x$
$\vec{\hat{H}}_i = \frac{\hat{E}_i}{\eta_0} e^{-j\beta_0 z}\vec{a}_y$	$\vec{\hat{H}}_r = -\frac{\hat{E}_r}{\eta_0} e^{j\beta_0 z}\vec{a}_y$	$\vec{\hat{H}}_1 = \frac{\hat{E}_1}{\hat{\eta}} e^{-\hat{\gamma} z}\vec{a}_y$	$\vec{\hat{H}}_2 = -\frac{\hat{E}_2}{\hat{\eta}} e^{\hat{\gamma} z}\vec{a}_y$	$\vec{\hat{H}}_t = \frac{\hat{E}_t}{\eta_0} e^{-j\beta_0 z}\vec{a}_y$

the phase constant and intrinsic impedance in the free-space regions are

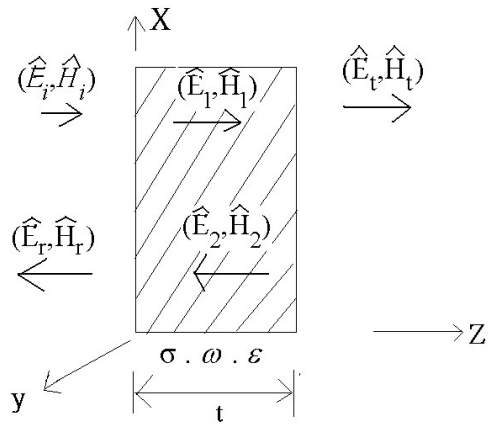
$$\beta_0 = \omega\sqrt{\mu_0\epsilon_0}$$

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$$

the propagation constant and intrinsic impedance of the shield are

$$\hat{\gamma} = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} = \alpha + j\beta$$

$$\hat{\eta} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} = \eta/\theta_\eta$$



The **exact expression** for the ratio of the incident electric field and the transmitted electric field

$$\frac{\hat{E}_i}{\hat{E}_t} = \frac{(\eta_0 + \hat{\eta})^2}{4\eta_0\hat{\eta}}\left[1 - \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)^2 e^{-2t/\delta} e^{-j2\beta t}\right] e^{t/\delta} e^{j\beta t} e^{-j\beta_0 t}$$

where $\delta = \frac{1}{\sqrt{\pi f \mu\sigma}}$ is the skin depth for the barrier material at the frequency of the incident wave

2 Shielding Effectiveness : Far-Field Sources

For shields that are constructed of good conductors, $\hat{\eta} \ll \eta_0$.
And shield thicknesses are much greater than a skin depth, $t \gg \delta$

Multiple-reflection loss can be neglected

$$M_{\text{dB}} = 20\log_{10}\left|1 - \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)^2 e^{-2t/\delta} e^{-j2\beta t}\right|$$

$$\cong 20\log_{10}\left|1 - e^{-2t/\delta} e^{-j2t/\delta}\right|$$

Shielding effectiveness (**approximate**)

$$\left|\frac{\hat{E}_i}{\hat{E}_t}\right| = \left|\frac{(\eta_0 + \hat{\eta})^2}{4\eta_0\hat{\eta}}\right| e^{t/\delta} \cong \left|\frac{\eta_0}{4\hat{\eta}}\right| e^{t/\delta}$$

$$\text{SE}_{\text{dB}} \cong \underbrace{20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right|}_{R_{\text{dB}}} + \underbrace{20\log_{10} e^{t/\delta}}_{A_{\text{dB}}}$$

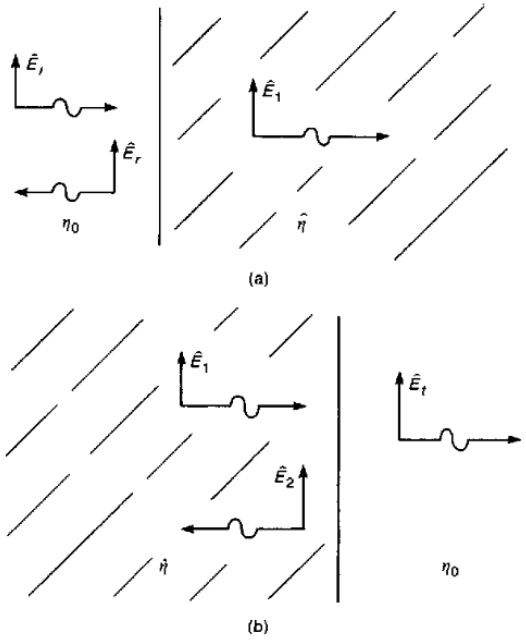
For barrier thicknesses that are thin compared with a skin depth, t<<δ, the multiple-reflection factor is negative (in dB). In this case, multiple reflections reduce the shielding effectiveness of the barrier.

For example, for $t/\delta = 0.1$, $M_{dB} = -11.8$ dB.

2 Shielding Effectiveness : Far-Field Sources

Approximate solution (cascaded concept)

A well-designed shield assumes that the barrier is constructed of a good conductor, $\hat{\eta} \ll \eta_0$, and the barrier thickness is much greater than a skin depth at the frequency of the incident wave, i.e., $t \gg \delta$.



Reflection Loss

transmission coefficient on left surface $\dfrac{\hat{E}_1}{\hat{E}_i} \cong \dfrac{2\hat{\eta}}{\eta_0 + \hat{\eta}}$

transmission coefficient on right surface $\dfrac{\hat{E}_t}{\hat{E}_1} \cong \dfrac{2\eta_0}{\eta_0 + \hat{\eta}}$

the ratio of the transmitted field and the incident field *without attenuation*

$$\frac{\hat{E}_t}{\hat{E}_i} = \frac{\hat{E}_t}{\hat{E}_1}\frac{\hat{E}_1}{\hat{E}_i} = \frac{2\eta_0}{\eta_0 + \hat{\eta}}\frac{2\hat{\eta}}{\eta_0 + \hat{\eta}} = \frac{4\eta_0\hat{\eta}}{(\eta_0 + \hat{\eta})^2}$$

Reflection loss term

$$R_{\text{dB}} = 20\log_{10}\left|\frac{\hat{E}_i}{\hat{E}_t}\right| = 20\log_{10}\left|\frac{(\eta_0 + \hat{\eta})^2}{4\eta_0\hat{\eta}}\right| \cong \boxed{20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right|}$$

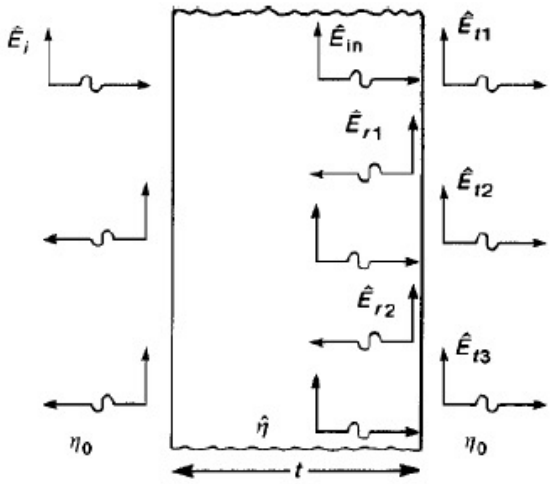
Absorption Loss

$$A_{\text{dB}} = 20\log_{10} e^{t/\delta}$$

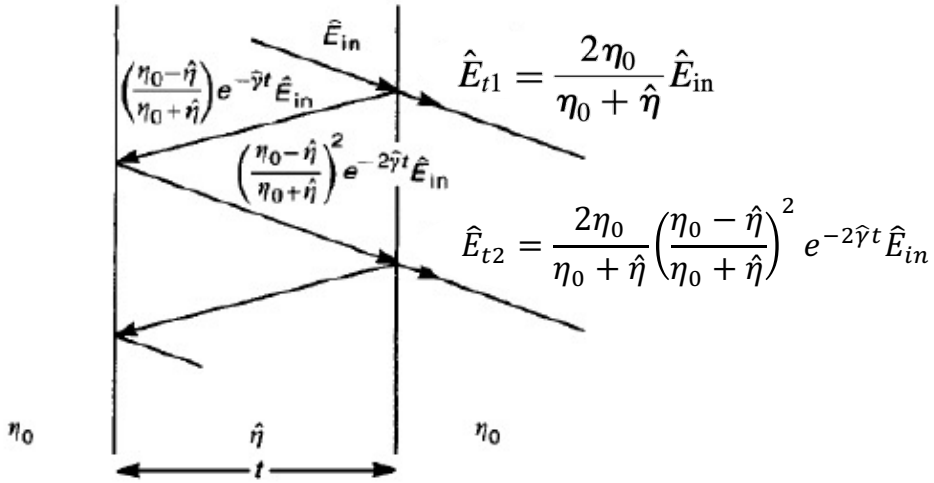
2 Shielding Effectiveness : Far-Field Sources

Approximate Solution (cascaded concept)

Multiple-Reflection Loss



combining multiple transmissions



calculation in terms of reflection and transmission coefficients

$$\hat{E}_t = \hat{E}_{t1}(1 + \Delta^2 + \Delta^4 + \cdots)$$

$$= \frac{\hat{E}_{t1}}{(1-\Delta^2)}$$

where $\Delta = \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)e^{-\hat{\gamma}t}$

valid for $|\Delta| < 1$

2. Shielding Effectiveness : Far-Field Sources

Approximate Solution (cascaded concept)

Total Loss

Substituting the approximation for the intrinsic impedance of a good conductor ($\frac{\sigma}{\omega\epsilon} \gg 1$)

$$\hat{\eta} \cong \sqrt{\frac{j\omega\mu}{\sigma}} \qquad \eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \qquad R_{\text{dB}} \cong 20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right|$$

Reflection Loss

$$R_{\text{dB}} = 20\log_{10}\left(\frac{1}{4}\sqrt{\frac{\sigma}{\omega\mu_r\epsilon_0}}\right)$$

For copper, $\sigma_{Cu} = 5.8\times10^7 S/m$. Other metals, $\sigma = \sigma_{Cu}\sigma_{\text{r}}$

$$R_{\text{dB}} = 168 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f}\right)$$

For copper, $R_{dB} = 138\ dB$ @ $1\ kHz, R_{dB} = 98\ dB$ @ $1\ MHz$.
For steel, $\mu_r = 1000$ and $\sigma_r = 0.1$. $R_{dB} = 98\ dB$ @ $1\ kHz, R_{dB} = 58\ dB$ @ $1\ MHz$.

2 Shielding Effectiveness : Far-Field Sources

Approximate Solution (cascaded concept)

Total Loss

Reflection Loss

$$R_{\text{dB}} = 20\log_{10}\left(\frac{1}{4}\sqrt{\frac{\sigma}{\omega\mu_r\epsilon_0}}\right)$$

$$R_{\text{dB}} = 168 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f}\right)$$

$$R_{\text{dB}} \cong 20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right|$$

Absorption Loss

$$A_{\text{dB}} = 20\log_{10} e^{t/\delta}$$

$$= \frac{20t}{\delta}\log_{10} e$$

$$= \frac{8.686t}{\delta}$$

$$= 131.4t\sqrt{f\mu_r\sigma_r} \quad (t \text{ in meters})$$

$$= 3.338t\sqrt{f\mu_r\sigma_r} \quad (t \text{ in inches})$$

Absorption Loss in terms of skin-depth

$$A_{\text{dB}} = \frac{8.686t}{\delta}$$

$$= 8.7 \text{ dB} \qquad \text{for } \frac{t}{\delta} = 1$$

$$= 17.4 \text{ dB} \qquad \text{for } \frac{t}{\delta} = 2$$

Q: is absorption loss increase by 10 dB/decade?



2 Shielding Effectiveness : Far-Field Sources

Total Loss

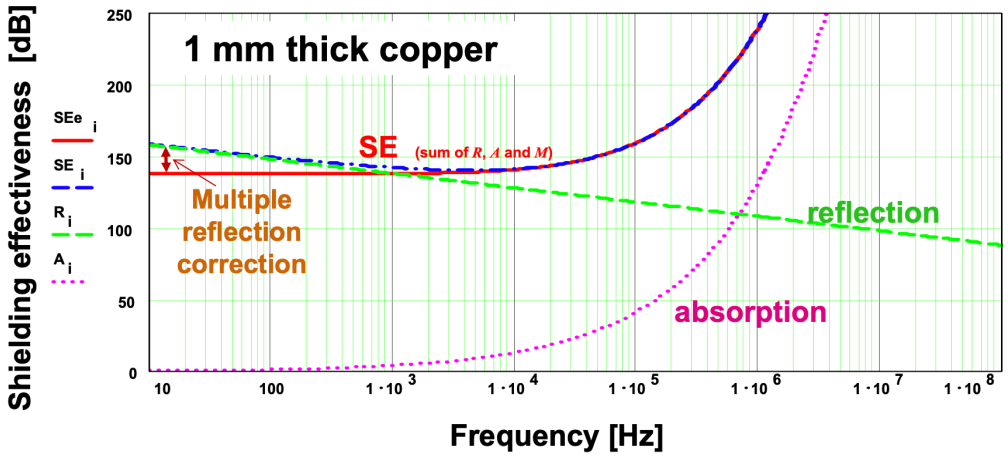
The reflection loss is a function of the ratio σ_r/μ_r, whereas the absorption loss is a function of the product $\sigma_r\mu_r$.

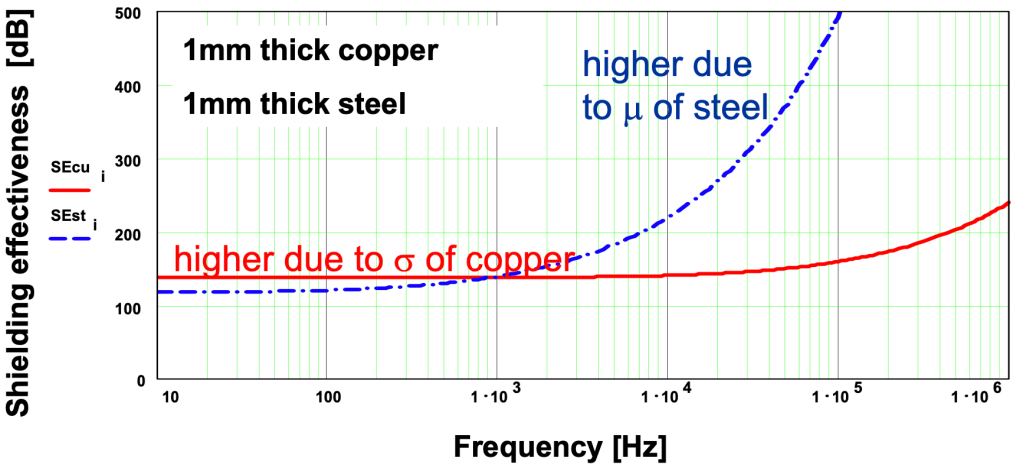
$$R_{\text{dB}} = 20\log_{10}\left(\frac{1}{4}\sqrt{\frac{\sigma}{\omega\mu_r\epsilon_0}}\right) \qquad A_{\text{dB}} = 131.4t\sqrt{f\mu_r\sigma_r}$$

Material	σ_r	μ_r	$A \sim \mu_r\sigma_r$	$R \sim \sigma_r/\mu_r$
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Gold	0.7	1	0.7	0.7
Aluminum	0.61	1	0.61	0.61
Brass	0.26	1	0.26	0.26
Bronze	0.18	1	0.18	0.18
Tin	0.15	1	0.15	0.15
Lead	0.08	1	0.08	0.08
Nickel	0.2	600	120	3.3×10^{-4}
Stainless steel (430)	0.02	500	10	4×10^{-5}
Steel (SAE 1045)	0.1	1000	100	1×10^{-4}
Mumetal (at 1 kHz)	0.03	30,000	900	1×10^{-6}
Superpermalloy (at 1 kHz)	0.03	100,000	3000	3×10^{-7}



2 Shielding Effectiveness : Far-Field Sources





Shielding effectiveness for a 1mm thickness of metal as a function of frequency

For far-field **(** uniform plane-wave**)** sources, reflection loss is the predominant shielding mechanism at the lower frequencies, while absorption loss is the predominant shielding mechanism at the higher frequencies.

Example 1: Calculating Shielding Effectiveness of Copper Foil

Calculate the shielding effectiveness of a sheet of 2-mil copper foil, $\sigma = 5.7\times10^7$ S/m, at 100 MHz.

Solution: skin depth in copper at 100 MHz $\delta_{cu} = 1/\sqrt{\pi f\mu\sigma} = 1/\sqrt{\pi(10^8)(4\pi\times10^{-7})(5.7\times10^7)} = 6.7\,\mu\text{m}$

material thickness (t = 2 mils = 50.8 μm), so $t \gg \delta_{cu}$

Absorption loss $A_{dB} \approx 8.868\left(\frac{t}{\delta}\right) = 8.868\left(\frac{50.8}{6.7}\right) = 66\ dB$

intrinsic impedance at 100 MHz $|\eta_{cu@100\,MHz}| = \sqrt{\frac{2\pi f\mu}{\sigma}} = \sqrt{\frac{2\pi(10^8)(4\pi\times10^{-7})}{5.7\times10^7}} = 3.7\times10^{-3}\ \Omega$

Reflection loss $R_{dB} = 20\log_{10}\frac{\eta_0}{4\hat{\eta}} = 20\log_{10}\frac{120\pi}{4(3.7\times10^{-3})} = 88\ dB$

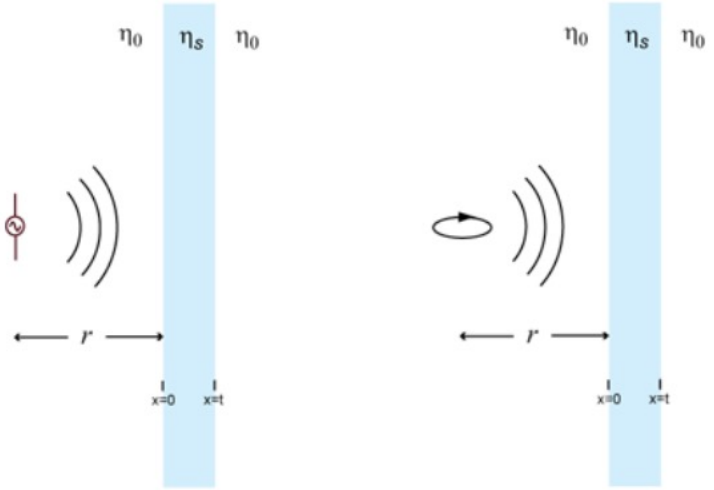
The overall shielding effectiveness

$$S.E. = 88\,dB + 66\,dB \approx 154\,dB$$



3 Shielding Effectiveness : Near-Field Sources

- The techniques for shielding depend on the type of source; whether the source is a magnetic field source or an electric field source.
- The heart of this approximate method is to replace the intrinsic impedance of free space, η_0, with the wave impedance, Z_w, for the Hertzian (electric) dipole and the small magnetic loop (dipole)
- Near Field versus Far Field:



Shielding electric and magnetic dipole sources.

the wave impedanc $\hat{Z}_w = \dfrac{\hat{E}_\theta}{\hat{H}_\phi} \Longleftrightarrow \dfrac{E_\theta}{H_\phi} = \eta_0$ in the far field

electric dipole $\hat{Z}_w = \eta_0 \dfrac{j/\beta_0 r + 1/(\beta_0 r)^2 - j/(\beta_0 r)^3}{j/\beta_0 r + 1/(\beta_0 r)^2}$ where $\beta_0 = 2\pi/\lambda_0$.

In the far field the $1/r$ terms dominate, giving $\hat{Z}_w \cong \eta_0$

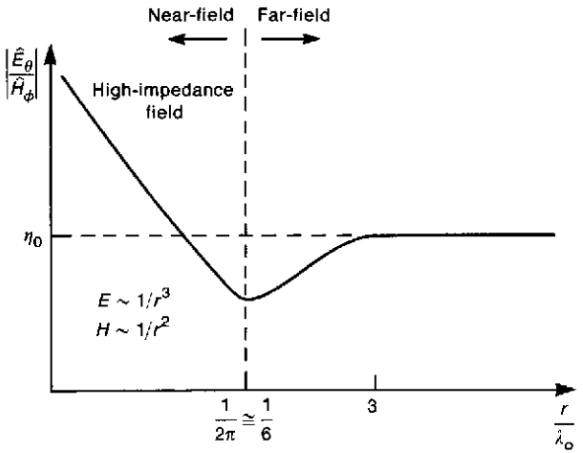
In the very near field $\hat{Z}_w \cong \eta_0 \left(-j\dfrac{1}{\beta_0 r}\right) = \dfrac{\eta_0}{\beta_0 r} \angle -90°$

(near field, $\beta_0 r \ll 1$)

3 Shielding Effectiveness: Near-Field Sources

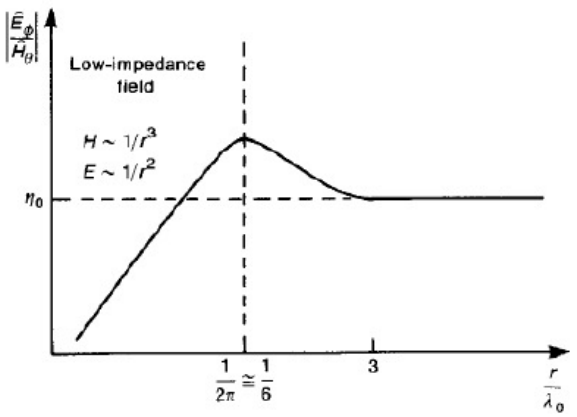
Wave Impedance in Near-Field

$$\hat{Z}_w = \frac{\hat{E}_\theta}{\hat{H}_\phi}$$



the electric (Hertzian) dipole

$$\hat{Z}_w = \eta_0 \frac{j/\beta_0 r + 1/(\beta_0 r)^2 - j/(\beta_0 r)^3}{j/\beta_0 r + 1/(\beta_0 r)^2}$$



the magnetic (loop) dipole

$$\hat{Z}_w = -\eta_0 \frac{j/\beta_0 r + 1/(\beta_0 r)^2}{j/\beta_0 r + 1/(\beta_0 r)^2 - j/(\beta_0 r)^3}$$

where $\eta_0 = \sqrt{\mu_0/\epsilon_0}$, $\beta_0 = \omega\sqrt{\mu_0 \epsilon_0}$, and $\beta_0 = 2\pi/\lambda_0$

3 Shielding Effectiveness: Near-Field Sources

Wave Impedance in Near-Field

$$\hat{Z}_w = \frac{\hat{E}_\theta}{\hat{H}_\phi}$$

the electric (Hertzian) dipole

$$\left.\begin{aligned}\hat{E}_\theta &\sim \frac{1}{r^3}\\ \hat{H}_\phi &\sim \frac{1}{r^2}\end{aligned}\right\}$$ (electric source, near field)

Near field $\hat{Z}_{we} \cong \eta_0\left(-j\frac{1}{\beta_0 r}\right) = \frac{\eta_0}{\beta_0 r}\angle -90°$

$$|\hat{Z}_w|_e = \frac{1}{2\pi f \epsilon_0 r} = 60\frac{\lambda_0}{r}$$

The electric dipole is referred to as a high-impedance source.

the magnetic (loop) dipole

$$\left.\begin{aligned}\hat{H}_\theta &\sim \frac{1}{r^3}\\ \hat{E}_\phi &\sim \frac{1}{r^2}\end{aligned}\right\}$$ (magnetic source, near field)

$\hat{Z}_{wm} \cong -j\eta_0\beta_0 r \cong \eta_0\beta_0 r\angle -90°$ Near field

$$|\hat{Z}_w|_m = 2\pi f \mu_0 r = 2369\frac{r}{\lambda_0}$$

The magnetic dipole is referred to as a low-impedance source.



3 Shielding Effectiveness: Near-Field Sources

The type of source is critical to determining effective shielding methodologies.

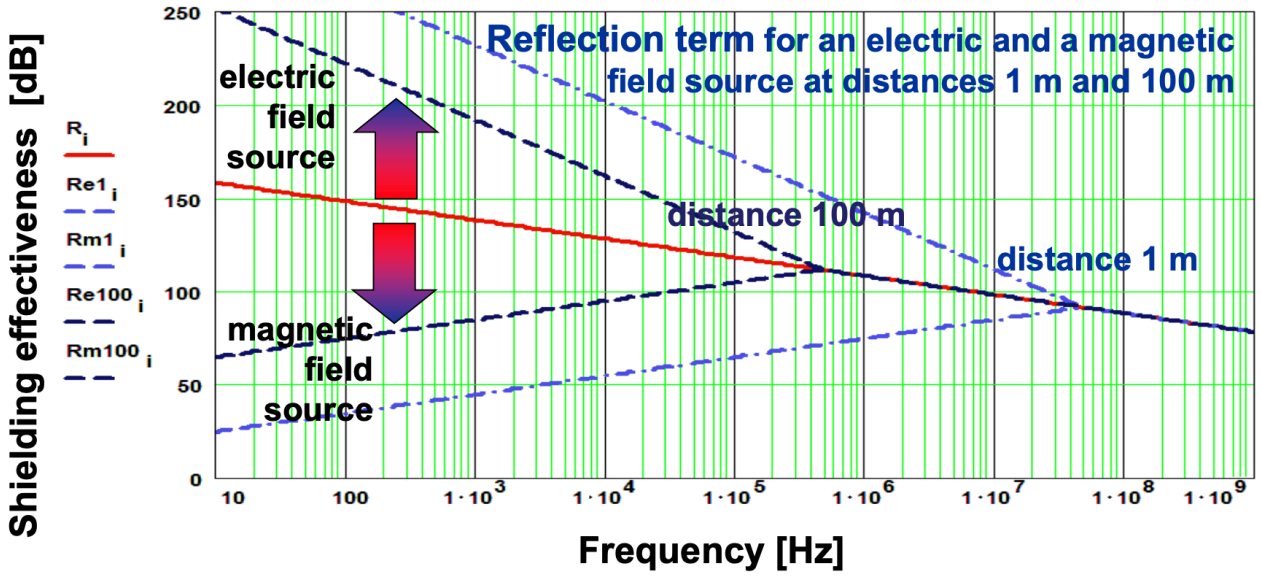
$$R_{\text{dB}} = 20\log_{10}\left|\frac{(\hat{Z}_w + \hat{\eta})^2}{4\hat{Z}_w\hat{\eta}}\right| \cong 20\log_{10}\left|\frac{\hat{Z}_w}{4\hat{\eta}}\right|$$

Electric Sources

$$R_{e,\text{dB}} = 322 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f^3 r^2}\right)$$

Magnetic Sources

$$R_{m,\text{dB}} = 14.57 + 10\log_{10}\left(\frac{f r^2 \sigma_r}{\mu_r}\right)$$



Reflection loss (far field)

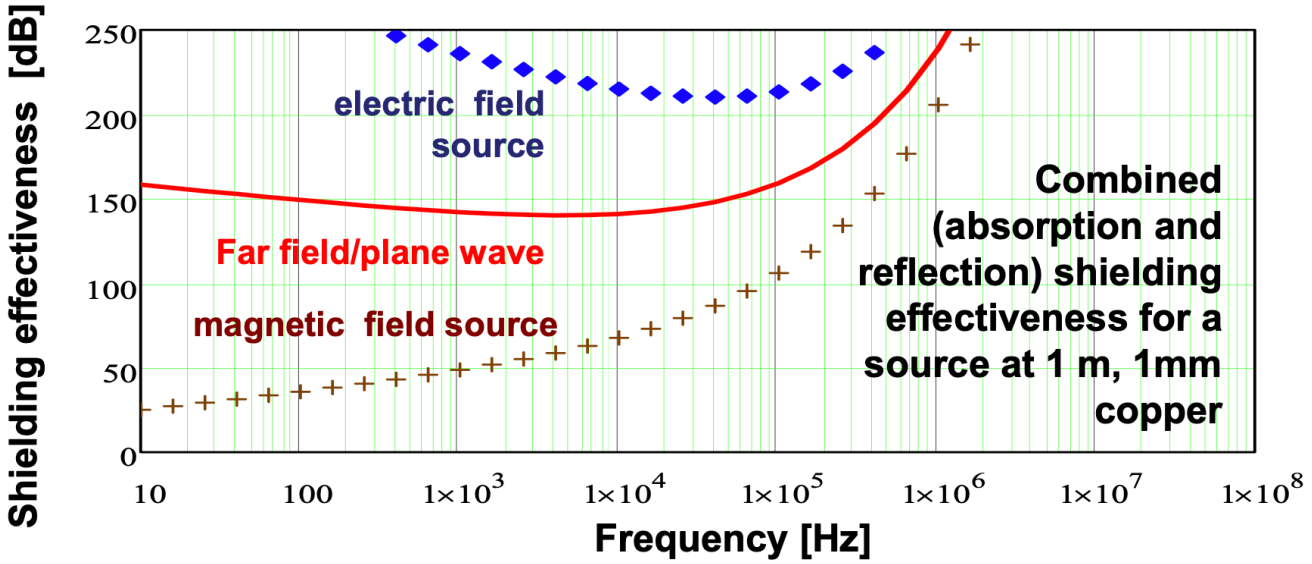
$$R_{\text{dB}} = 168 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f}\right)$$

Absorption loss

$$\begin{aligned} A_{\text{dB}} &= 20\log_{10} e^{t/\delta} \\ &= \frac{20t}{\delta}\log_{10} e \\ &= \frac{8.686t}{\delta} \\ &= 131.4t\sqrt{f\mu_r\sigma_r} \quad (t \text{ in meters}) \\ &= 3.338t\sqrt{f\mu_r\sigma_r} \quad (t \text{ in inches}) \end{aligned}$$

Reflection loss of near-field electric and magnetic sources for a copper shield

3 Shielding Effectiveness: Near-Field Sources



Near-field E source can be shielded easily with a (thin) metal sheets
Near-field low frequency H source can't be shielded this way

- we need thick material for absorption term, and
- the reflection term is low for magnetic field sources,
- ➔ more difficult

Example 2: Shielding a Low-Frequency Magnetic Field Source

A transformer generating primarily a magnetic field is located 10 cm from a shielding structure. The shielding structure is made from a 1-cm thick sheet of copper. Estimate the shielding effectiveness of this structure at 1.5 kHz.

Solution: We can treat the transformer as a magnetic dipole source

the wave impedance $|\hat{Z}_{wm}| \approx 2\pi f \mu_0 r = 2\pi\,(1.5\times10^{3})\,(4\pi\times10^{-7})\,(0.10) = 1.2\times10^{-3}\,\Omega.$

The intrinsic impedance and skin depth of the copper are,

$$|\eta_{cu@1.5\,kHz}| = \sqrt{\frac{2\pi f\mu}{\sigma}} = \sqrt{\frac{2\pi(1.5\times10^{3})(4\pi\times10^{-7})}{5.7\times10^{7}}} = 14\times10^{-6}\,\Omega$$

$$\delta_{cu} = 1\Big/\sqrt{\pi f\mu\sigma} = 1\Big/\sqrt{\pi(1.5\times10^{3})(4\pi\times10^{-7})(5.7\times10^{7})} = 1.7\,\text{mm}.$$

shielding effectiveness

$$S.E. = 20\log\frac{0.0012}{4(14\times10^{-6})} + 20\log e^{10/1.7} + 20\log\left|1+e^{-2\left(10/1.7\right)}\right|$$

$$= 26\,\text{dB} + 51\,\text{dB} + \sim0\,\text{dB}$$

$$= 77\,\text{dB}$$



4 Low-Frequency, Magnetic Field Shielding

- For far-field (uniform plane-wave) sources, reflection loss is the predominant shielding mechanism at the lower frequencies, while absorption loss is the predominant shielding mechanism at the higher frequencies.
- For near-field, electric sources, reflection loss is predominant at the lower frequencies, while absorption loss is predominant at the higher frequencies.
- For near-field, magnetic sources, the situation is quite different at low frequencies. Absorption loss tends to be the dominant shielding mechanism for near-field, magnetic sources at all frequencies.

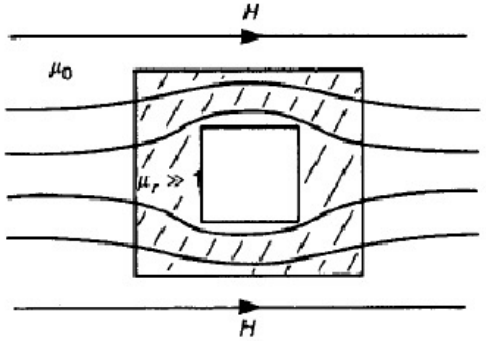
There are two basic methods for shielding against low-frequency, magnetic sources:

1. *diversion of the magnetic flux with high-permeability materials* μ
2. *generation of opposing flux via Faraday's law, commonly known as the "shorted turn method."*

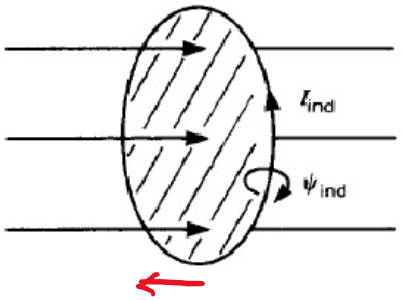


4 Low-Frequency, Magnetic Field Shielding

Two important methods of shielding against low-frequency magnetic fields:



using a highly permeable ferromagnetic material to divert the magnetic field



using a "shorted turn" of conductor to generate an opposing magnetic field

There are two factors that may degrade the effectiveness of the flux diversion technique and must be kept in mind:

1. The permeability of ferromagnetic materials decreases with increasing frequency.
2. The permeability of ferromagnetic materials decreases with increasing magnetic field strength.

4 Low-Frequency, Magnetic Field Shielding

Illustration of the frequency dependence of various ferromagnetic materials

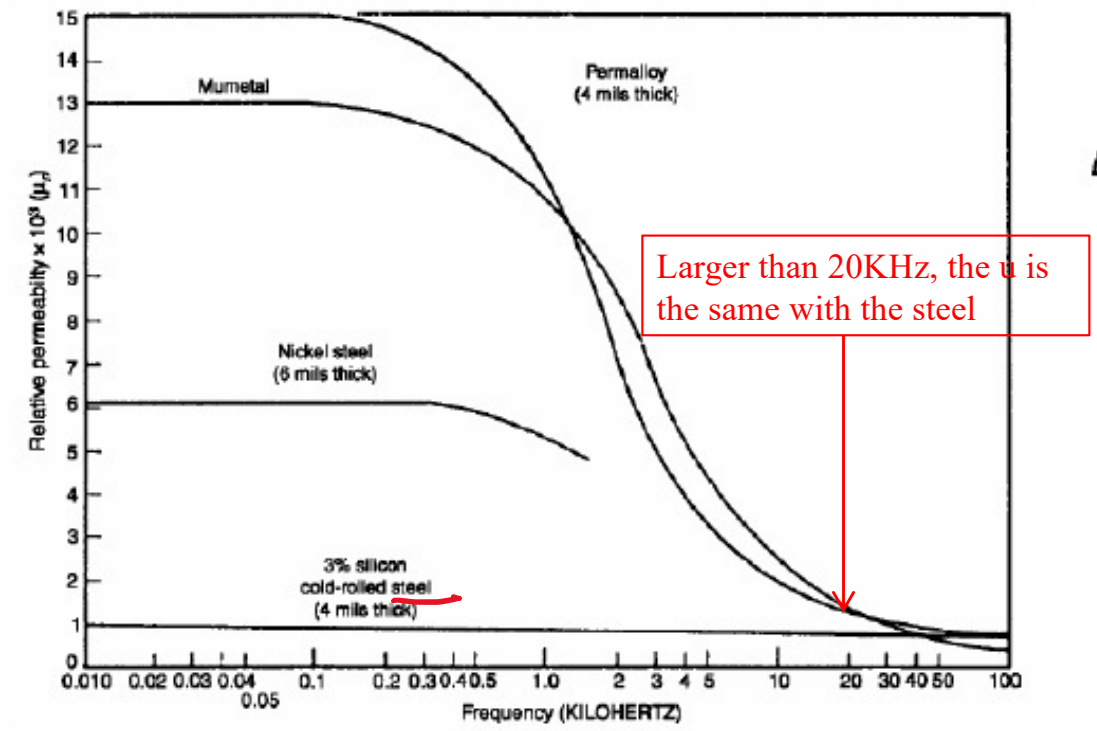
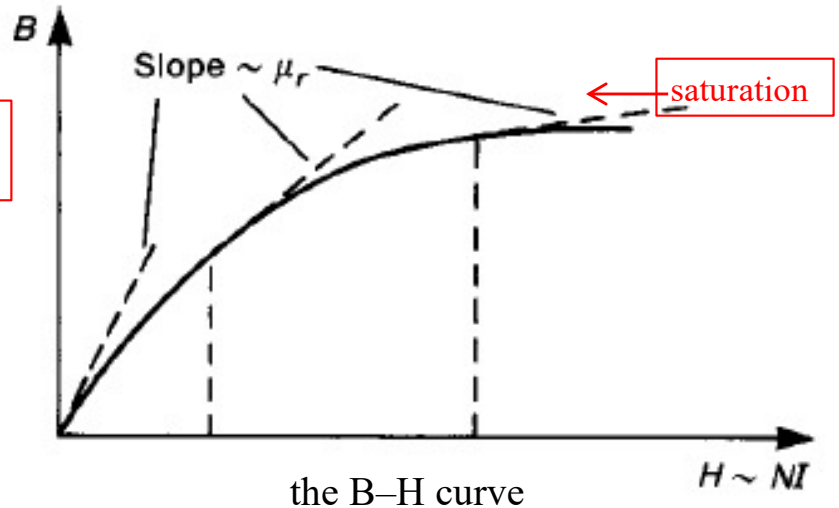


Illustration of the important phenomenon of saturation of ferromagnetic materials:

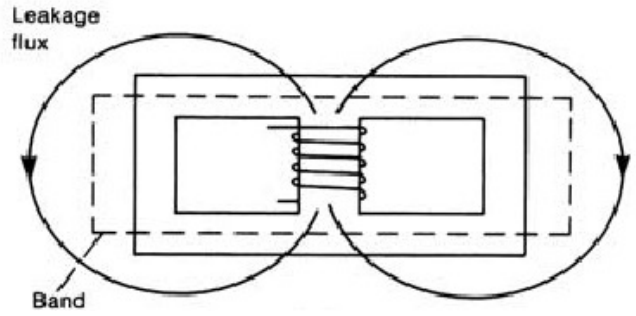


the B–H curve

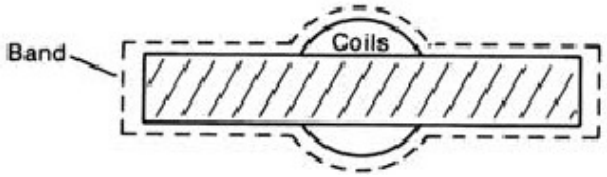
Solution: use of a multilayer magnetic shield to reduce the effects of saturation

4 Low-Frequency, Magnetic Field Shielding

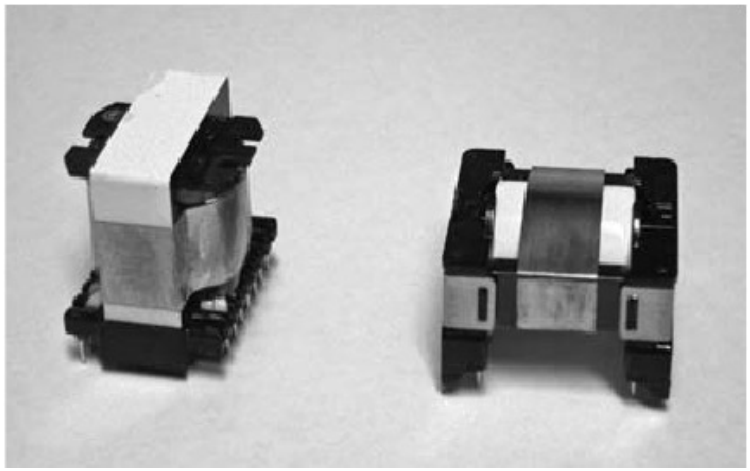
Use of the shorted-turn effect (bands) to reduce the radiated magnetic fields of transformer leakage flux:



side view



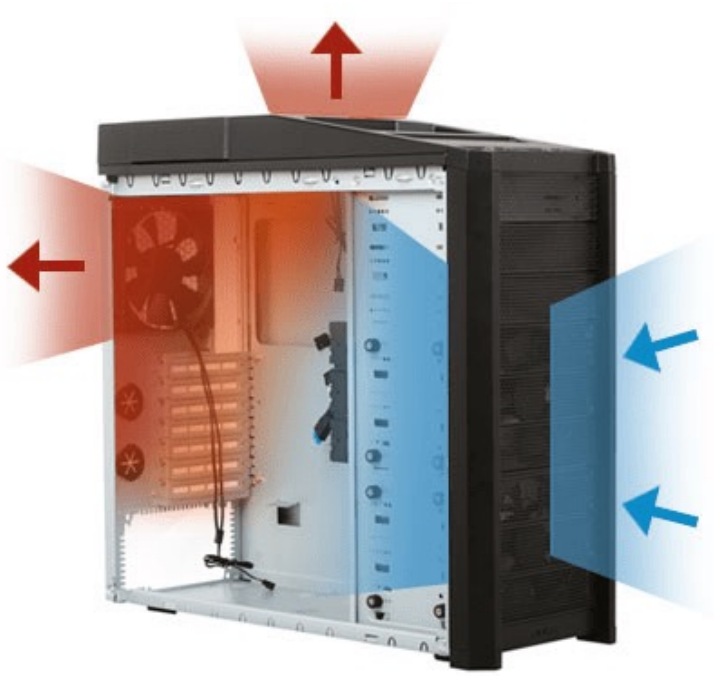
top view



Photograph of bands on a switching transformer used to reduce the radiated magnetic field

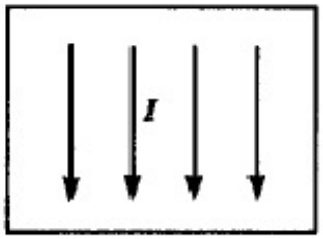
5 Effects of Apertures

- There are numerous cases where openings in an otherwise contiguous shield cannot be avoided for practical reasons.
  - One of the more common ones is the need to ventilate the internal electronics for thermal reasons. Fans are frequently employed to move hot air inside the shield to the outside.
  - One will observe that these types of openings are frequently in the form of a large number of small holes rather than one large hole.
  - Many small holes provide as much ventilation as does one long slot, but perturb the induced current much less, thereby reducing the degradation caused by the aperture

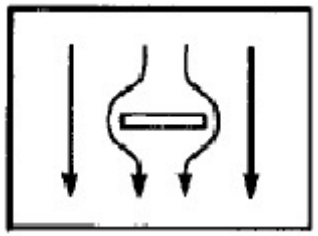


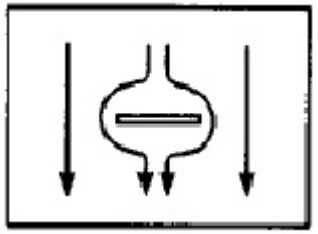
5 Effects OF Apertures

Illustration of the effects of slots on induced currents on shields.

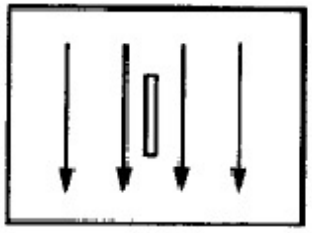


(a) Consider the solid shield. Currents are induced to flow in this shield

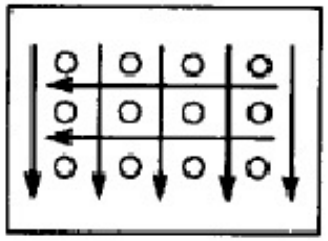




(b) The slot will interrupt the current flow, and will tend to reduce the shielding effectiveness. The width of the slot does not significantly affect this.



(c) If we orient the slot parallel to the direction of the induced current, the slot will have much less effect on the shielding



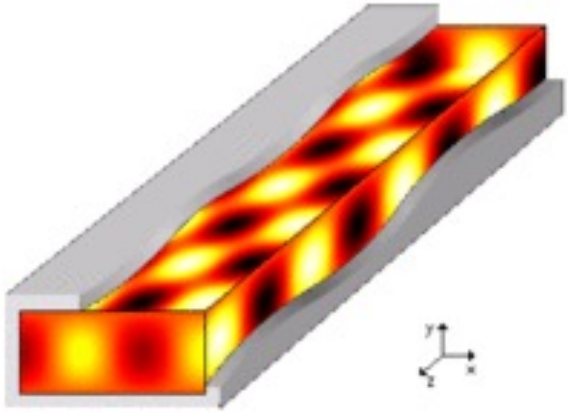
(d) large number of small holes are used instead determination the direction of the induced current

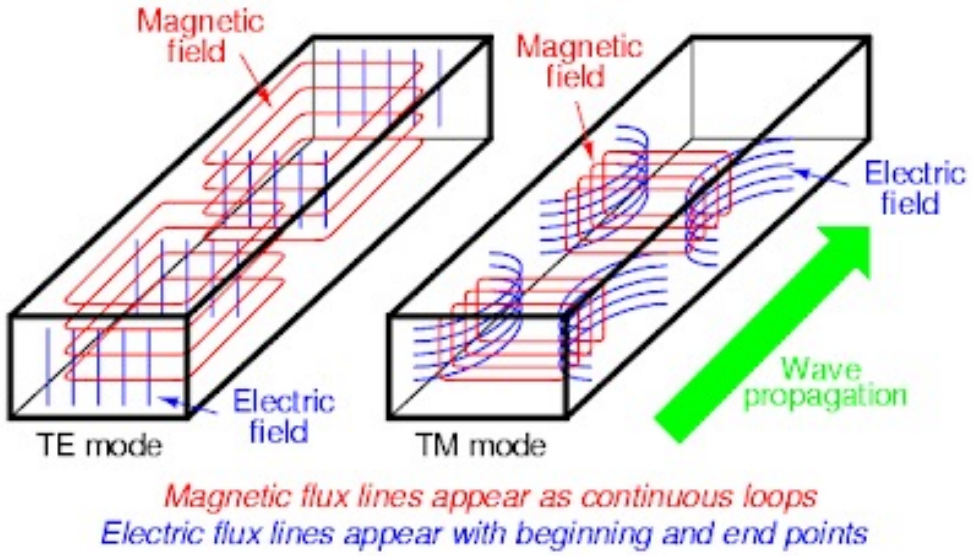
5 Effects OF Apertures

Openings in shielded enclosures can be protected by “waveguide above cutoff” principle

A square waveguide with side dimensions d has a cutoff frequency for the propagation of higher-order modes TE_{mn} and TM_{mn}

$$f_{c,mn} = \frac{v_0}{2d}\sqrt{m^2 + n^2}$$





Magnetic flux lines appear as continuous loops
Electric flux lines appear with beginning and end points

5 Effects OF Apertures

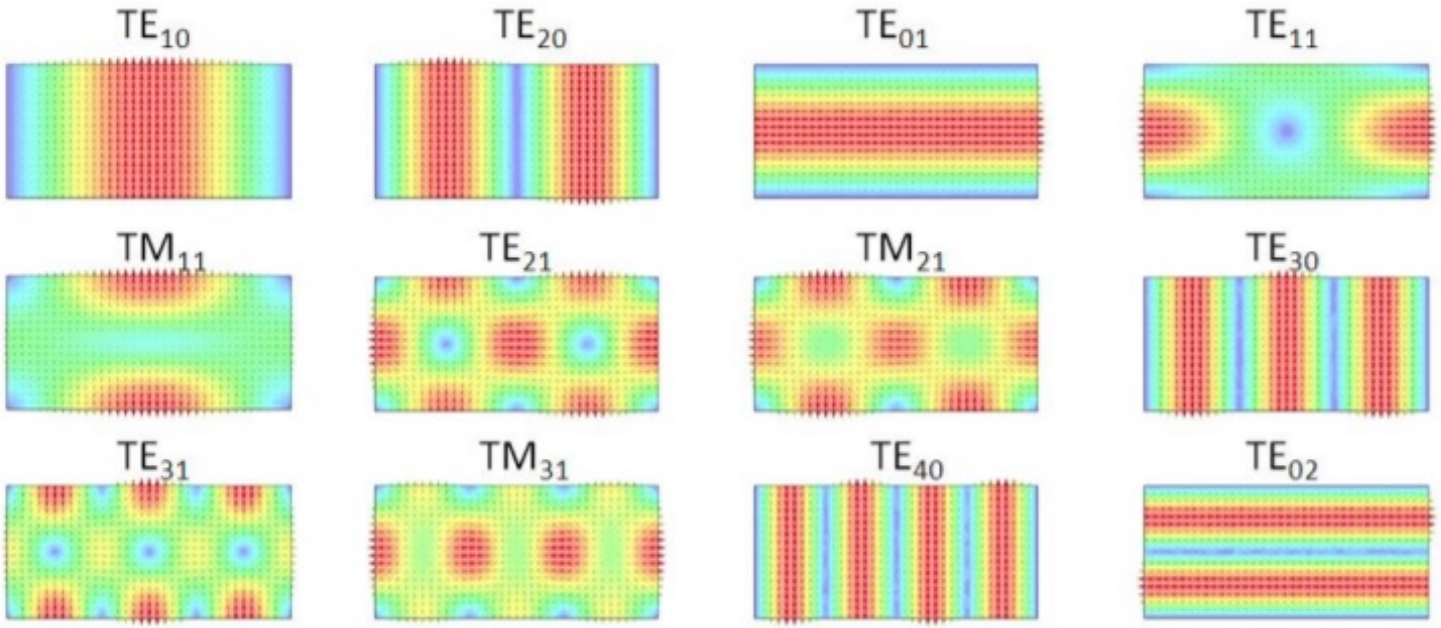


Fig. 5: The first 12 modes in a rectangular waveguide. The arrows of the electric fields are sketched

The lowest-order propagating mode is the TE_{10} mode

5 Effects OF Apertures

- In actual products we have apertures, or holes
- A simple aperture is ‘open’ if the diameter equals a half-wavelength $d=\lambda/2$





$$SE_{hole} = 20\log\left(\frac{\lambda/2}{d}\right)$$

$$= 20\log\left(\frac{\lambda}{2d}\right)$$

- This results in a reduction of the shielding effectiveness (compared to infinite large plate)

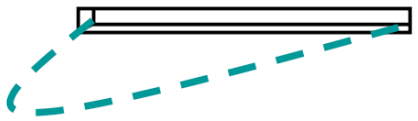
5 Effects OF Apertures

Example: aperture of 1000 mm^2

$$SE_{hole} = 20\log\left(\frac{\lambda}{2d}\right)$$



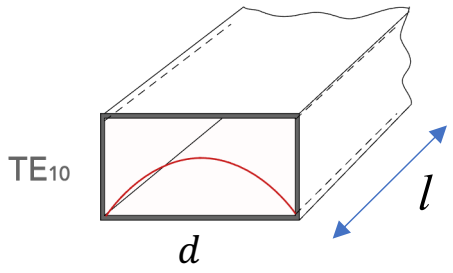
- Circular, radius 18mm, so d=36mm. So if λ=72mm, which is at 4.17 GHz, then 0 dB



- Rectangular, 165 mm x 6 mm (DVD). So if λ =330mm, which is at 900 MHz (GSM frequency), then 0 dB

5 Effects OF Apertures – Depth of Aperture

The lowest-order propagating mode is the TE10 mode, with cutoff frequency



$$f_{c,10} = \frac{v_0}{2d}$$
$$= \frac{1.5 \times 10^8}{d} \quad (d \text{ in m})$$
$$= \frac{5.9 \times 10^9}{d} \quad (d \text{ in inches})$$

The attenuation of a rectangular waveguide to these higher-order modes

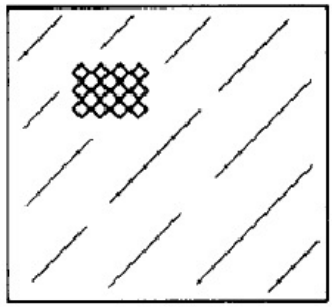
$$\alpha_{mn} = \omega\sqrt{\mu_0\epsilon_0}\sqrt{\left(\frac{f_{c,mn}}{f}\right)^2 - 1} \quad \Rightarrow \quad \alpha_{mn} \cong \frac{2\pi f}{v_0}\frac{f_{c,mn}}{f} \quad f \ll f_{c,mn}$$
$$= \frac{2\pi f_{c,mn}}{v_0}$$

effective attenuation constant

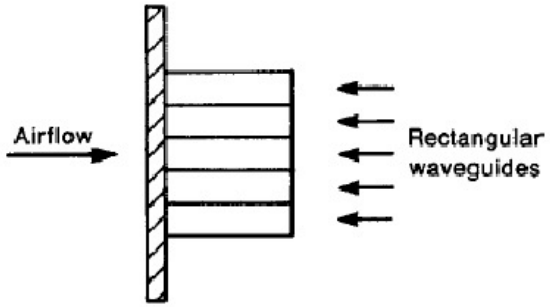
For TE_{10} mode, $\boxed{\alpha_{10} = \frac{\pi}{d}}$

5 Effects OF Apertures – Depth of Aperture

Use of the waveguide-below-cutoff principle to provide ventilation of an enclosure and to minimize the electromagnetic field penetrations



front view



Side view

For the lowest-order TE10

$$\alpha_{10} = \frac{\pi}{d} \Rightarrow$$

$$\begin{aligned} \mathrm{SE_{dB}} &= 20 \log_{10} e^{\alpha_{10} l} \\ &= \alpha_{10} l \, 20 \log_{10} e \\ &= 27.3 \frac{l}{d} \end{aligned}$$

The attenuation of a guide of length l is proportional to $e^{-\alpha l}$.

5 Effects OF Apertures – Depth of Aperture

Two cases:

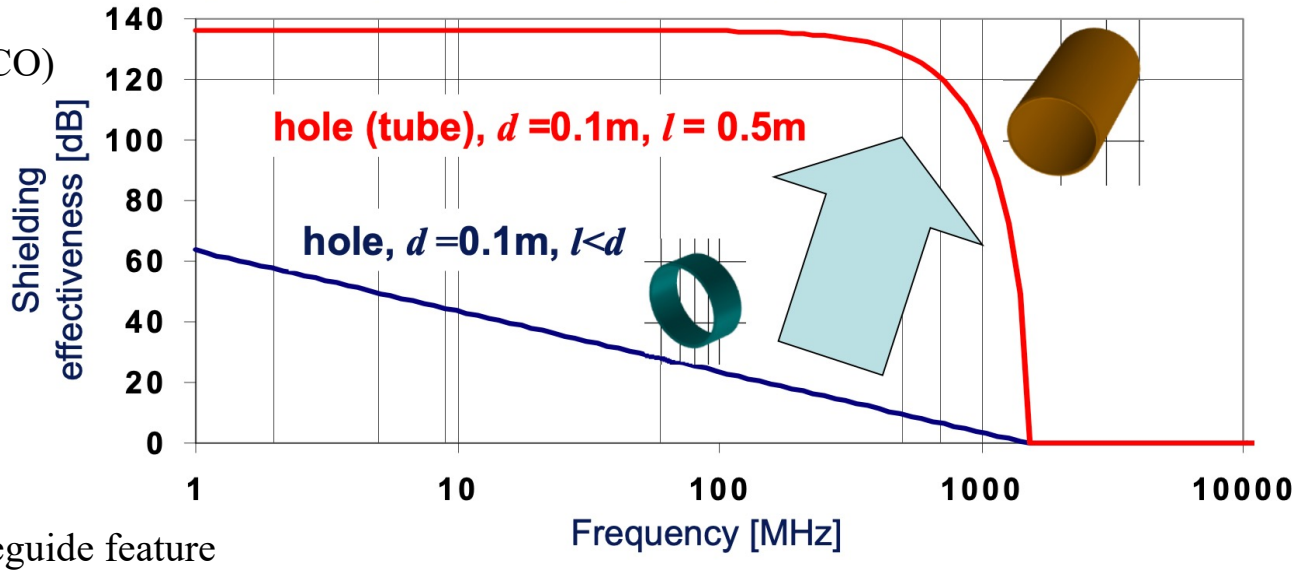
- hole $l>d$ (red curve)
  - Waveguide beyond cut off (WBCO)
  - Constant when f small, d>λ/2

$$\begin{aligned} SE_{dB} &= 20\log_{10} e^{\alpha_{10} l} \\ &= \alpha_{10} l \, 20\log_{10} e \\ &= 27.3\frac{l}{d} \end{aligned}$$

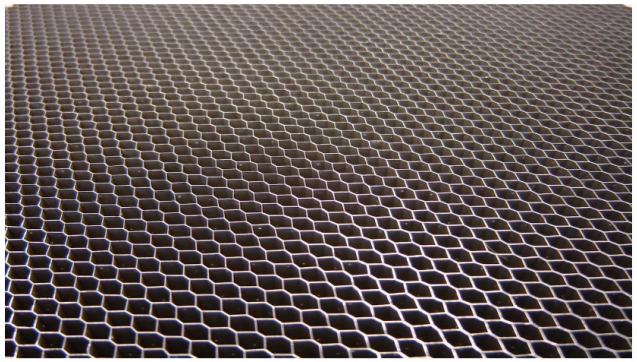
- hole $l<d$ (blue curve)
  - hollow aperture
  - Acting like λ/2 antenna, no waveguide feature

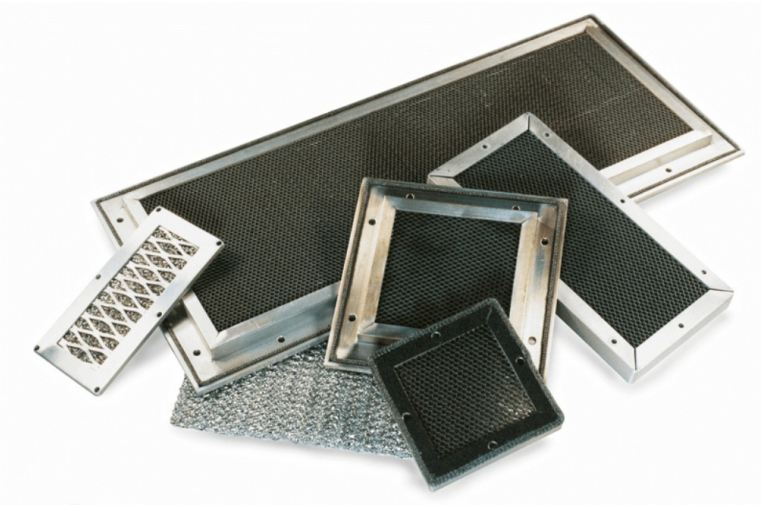
$$SE_{hole} = 20\log\left(\frac{\lambda}{2d}\right)$$

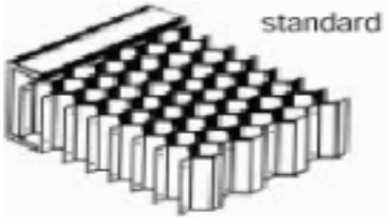
➡ waveguide-beyond-cut-off (WBCO)

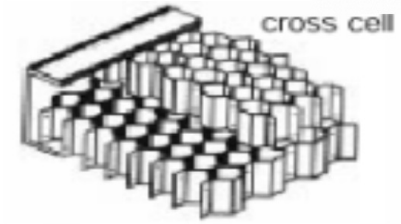


Honeycomb ventilation panels









Poll:

The shielding effectiveness of an enclosure (with apertures) made of a material that has a plane-wave shielding effectiveness of 60 dB is,

A. ~60 dB
B. Always less than 60 dB
C. Usually greater than 60 dB
D. Sometimes less than 0 dB



Summary about shielding theory

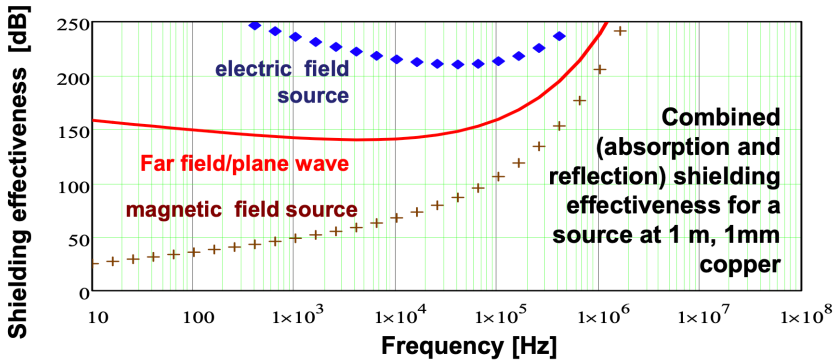
- Shielding effectiveness infinite large plates is very high
- Shielding of
  - dominant magnetic fields starts low, and is increasing with frequency
  - plane waves and electric fields starts high and is decreasing with frequency

•To shield, for

magnetic sources you need thick, high μ material
electric and plane wave (thin) highly conducting (σ) materials needed

•Examples

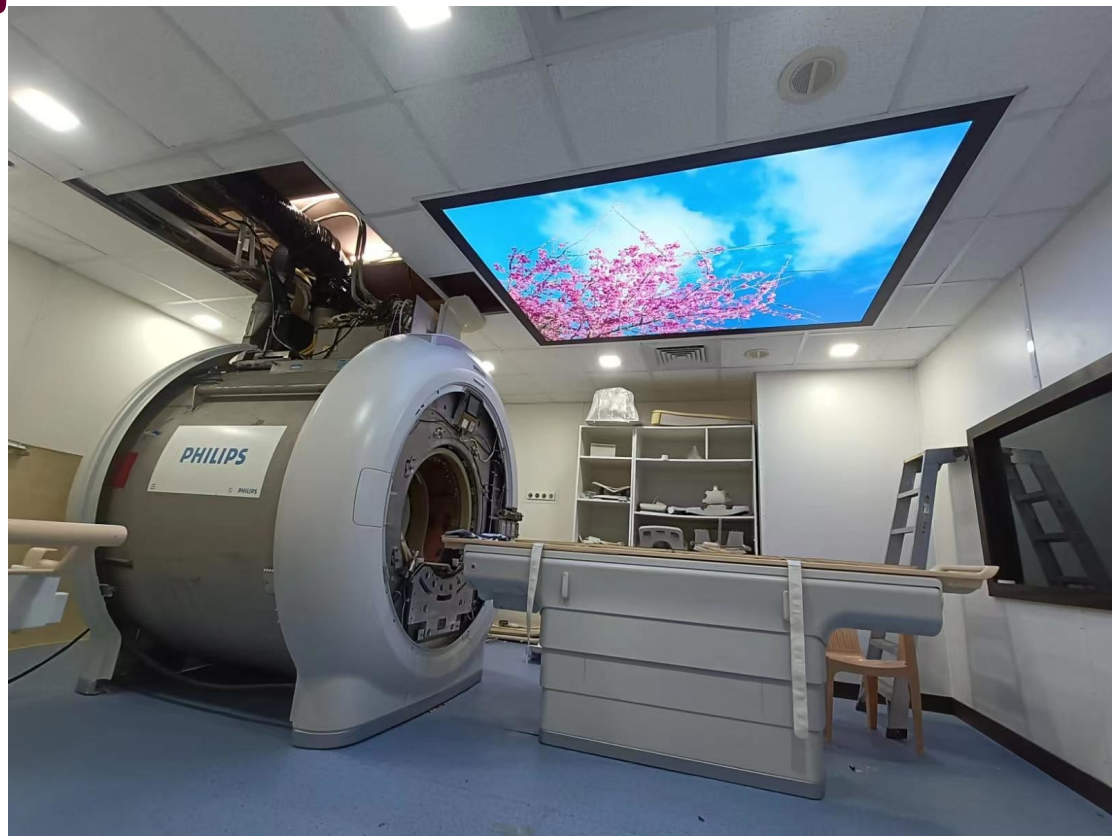
magnetic: iron (μ) around a switched mode power supply
electric: thin gold (σ) on glass window



Thin coating, highly reflecting



Shielded screen on medical devices



Faraday Cage MRI Room Copper Shielding

Thick coating, absorbing



Mu-metal shielding





