ILLINOIS
Electrical & Computer Engineering
GRAINGER COLLEGE OF ENGINEERING

Shielding

Prof. Victoria Shao

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

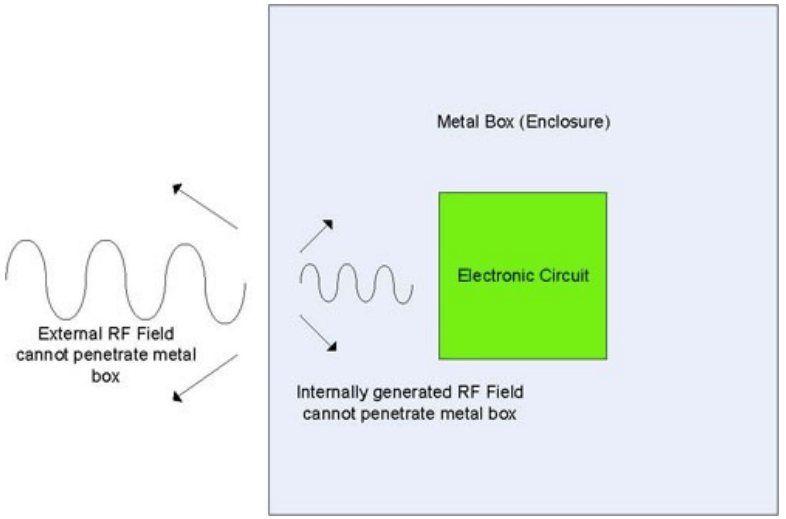
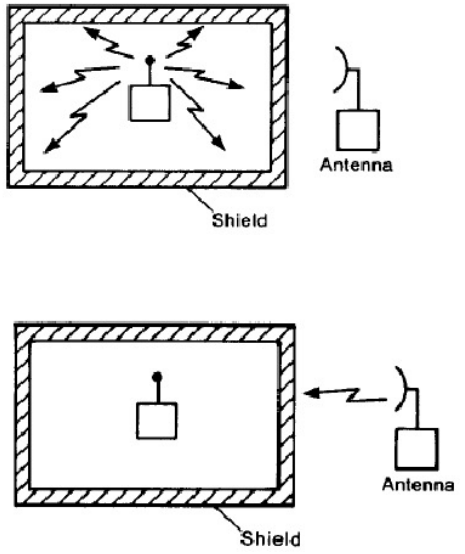


Illustration of the use of a shielded enclosure

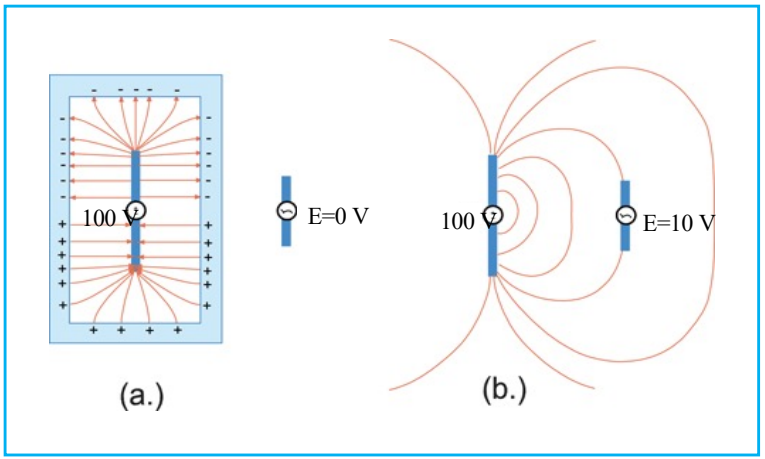
1 Shielding

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

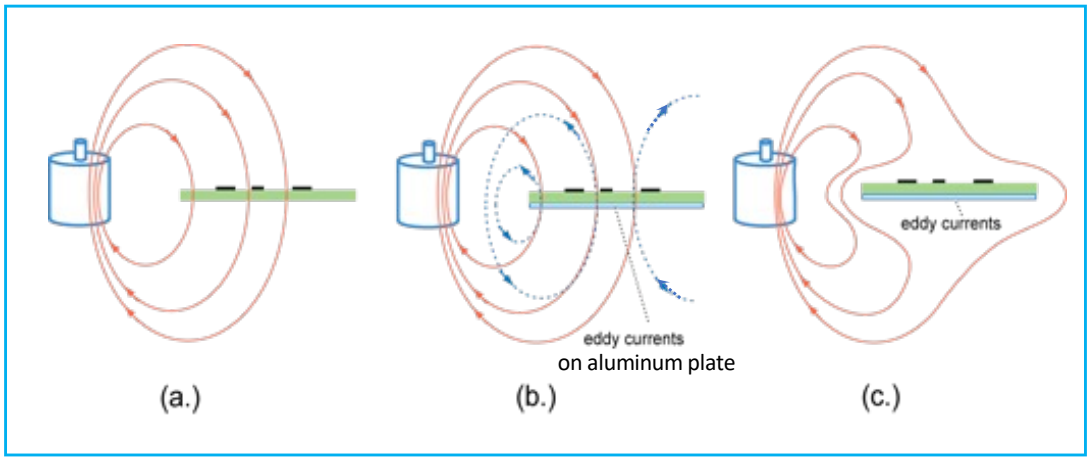
- Purposes of a shield
  - ✓ To prevent the emissions from the electronics radiating outside the boundaries of the product.
    - prevent those emissions from causing the product to fail to comply with the radiated emissions limits
    - prevent the product from causing interference with other electronic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

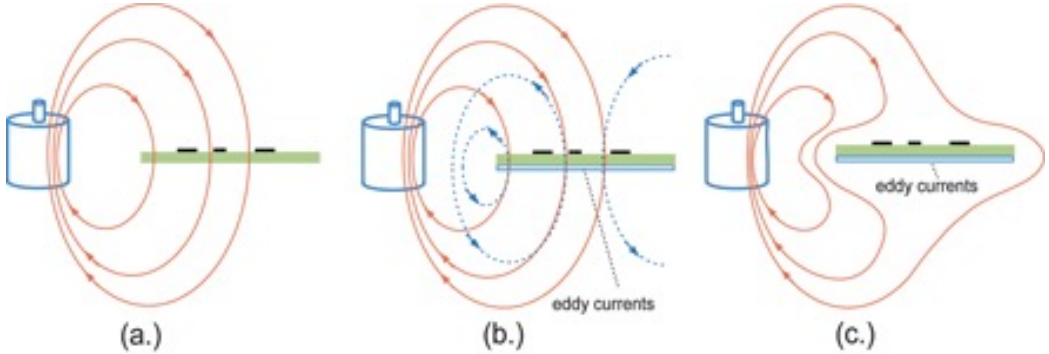


Before

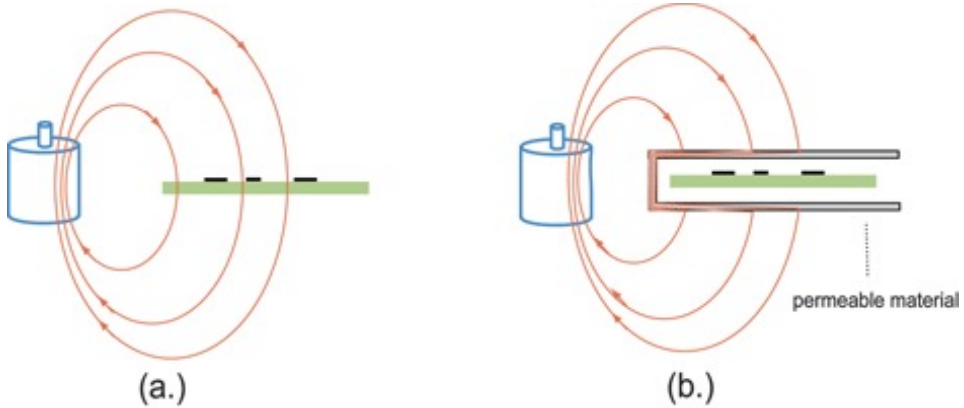
After

(c.)

Magnetic field shielding examples



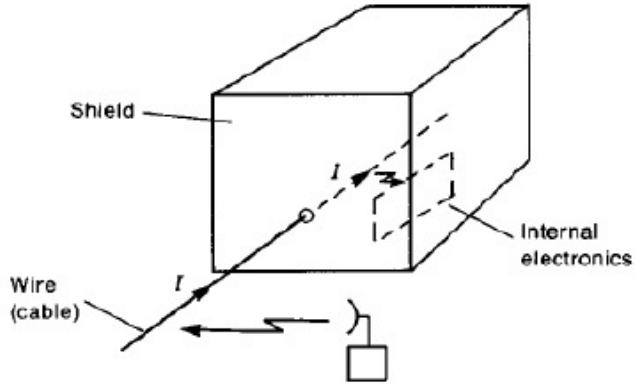
Magnetic field shielding with good conductors



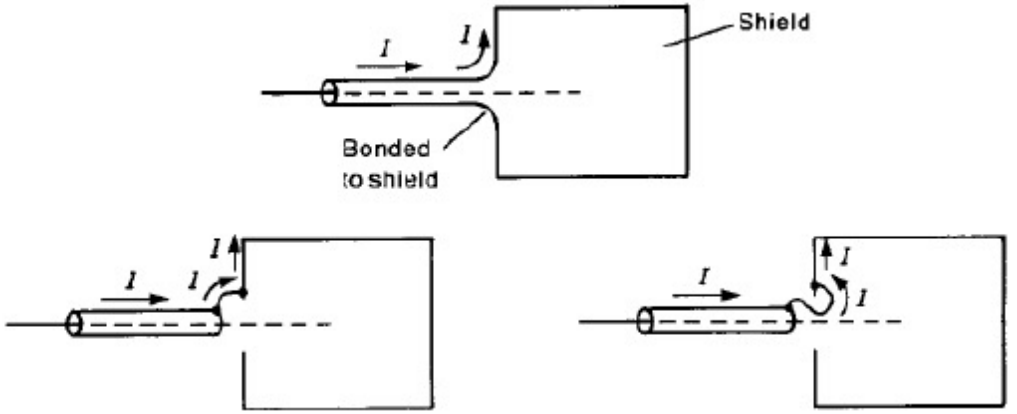
Magnetic field shielding with magnetic materials

Shielding

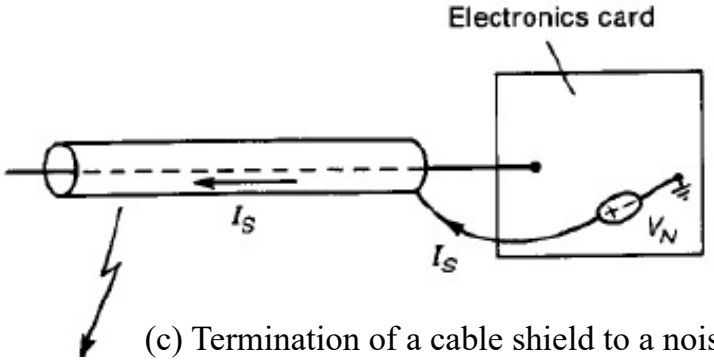
Important practical considerations that seriously degrade shielding effectiveness



(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

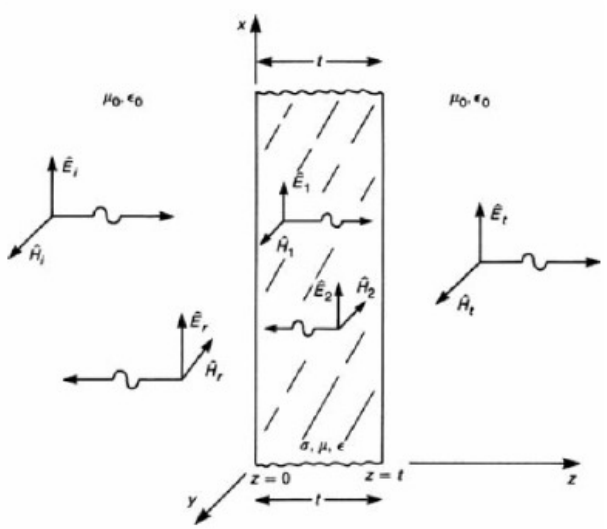


(c) Termination of a cable shield to a noisy point, causing the shield to radiate

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 ?

① Same medium on both side.

② far field

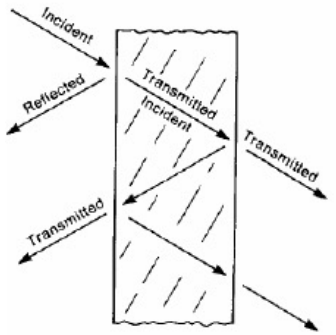


Illustration of multiple reflections within a shield.

Shielding effectiveness =
reflection loss + absorption loss + multiple reflections

$$\mathrm{SE_{dB}} = R_{\mathrm{dB}} + A_{\mathrm{dB}} + M_{\mathrm{dB}}$$

not t on t. negative.

2 Shielding Effectiveness : Far-Field Sources

far. field.

phasor

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

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

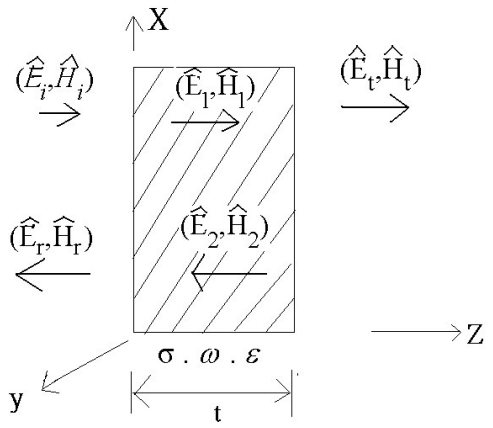
$$\beta_0 = \omega\sqrt{\mu_0\epsilon_0}$$

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

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

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

Multiple Reflection. Absorption

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**)

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

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

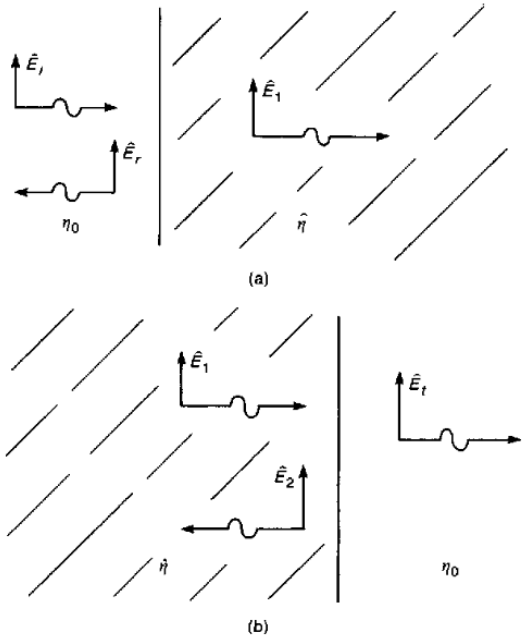
For barrier thicknesses that are thin compared with a skin depth, t<<δ, the multiple-reflection factor is negative (in dB). In this case, multiple reflections reduce the shielding effectiveness of the barrier.

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

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

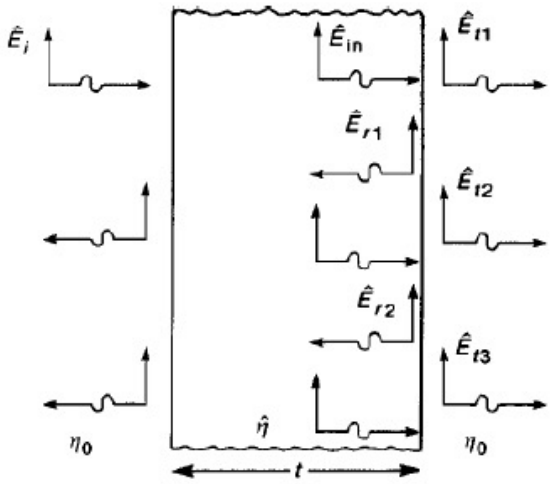
Absorption Loss

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

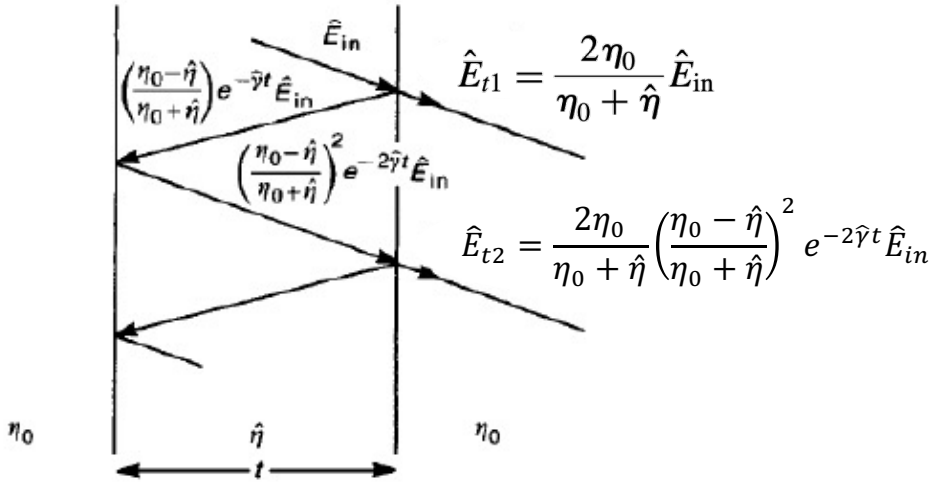
2 Shielding Effectiveness : Far-Field Sources

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

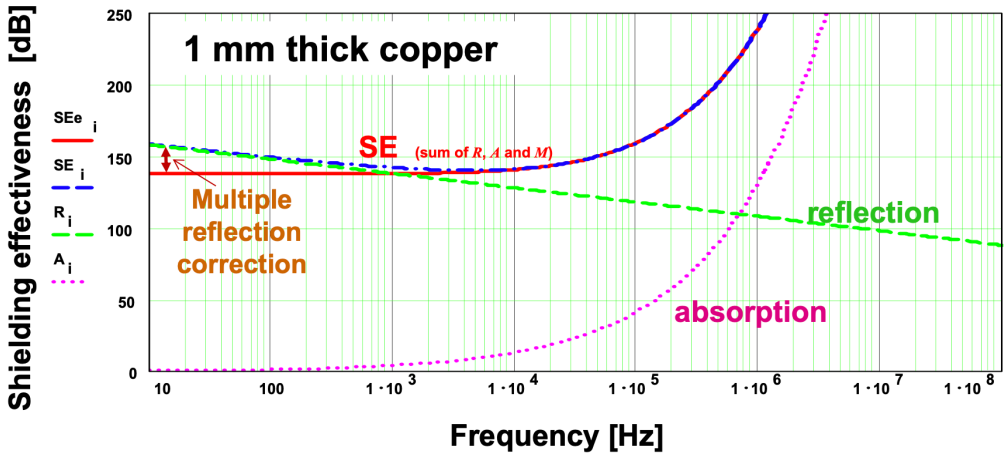
The reflection loss is a function of the ratio σ_r/μ_r, whereas the absorption loss is a function of the product $\sigma_r\mu_r$.

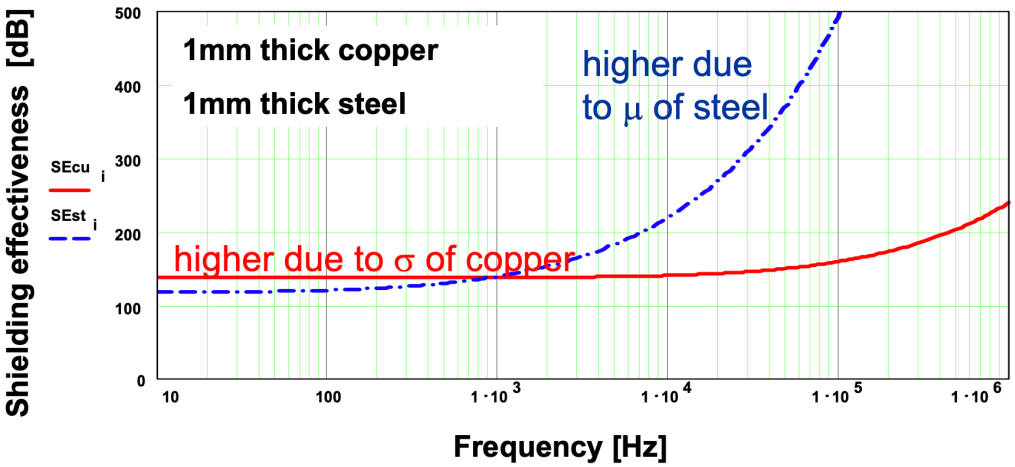
$$R_{\text{dB}} = 20\log_{10}\left(\frac{1}{4}\sqrt{\frac{\sigma}{\omega\mu_r\epsilon_0}}\right) \qquad A_{\text{dB}} = 131.4t\sqrt{f\mu_r\sigma_r}$$

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, $\sigma = 5.7\times107$ 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 $R_{dB} = 20\log_{10}\frac{\eta_0}{4\hat{\eta}} = 20\log_{10}\frac{120\pi}{4(3.7\times10^{-3})} = 88\,dB$

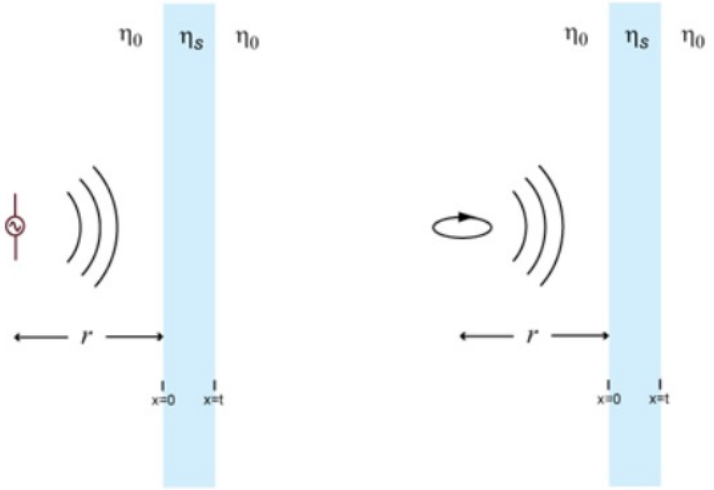
The overall shielding effectiveness

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



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 $\hat{Z}_w \cong \eta_0$

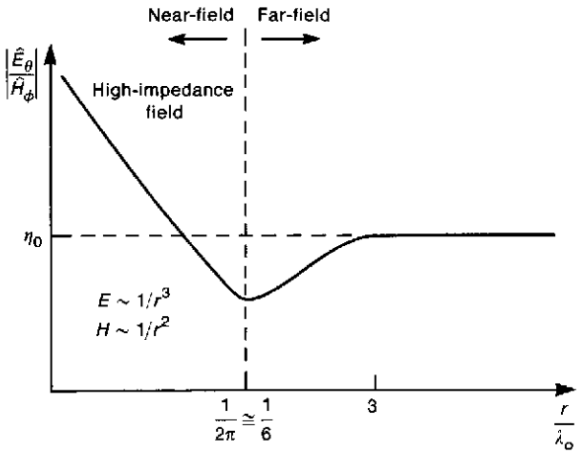
In the very near field $\hat{Z}_w \cong \eta_0 \left(-j\dfrac{1}{\beta_0 r}\right) = \dfrac{\eta_0}{\beta_0 r} \angle -90°$

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

3 Shielding Effectiveness: Near-Field Sources

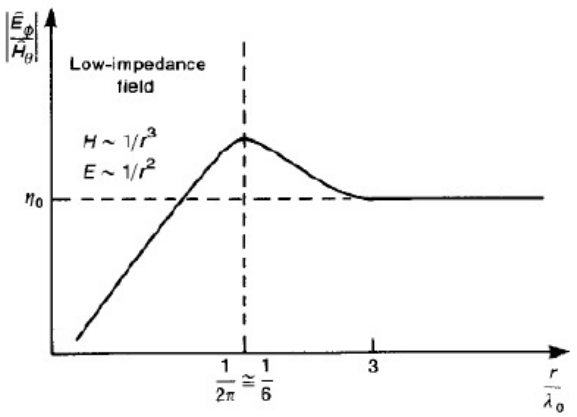
Wave Impedance in Near-Field

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



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.

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

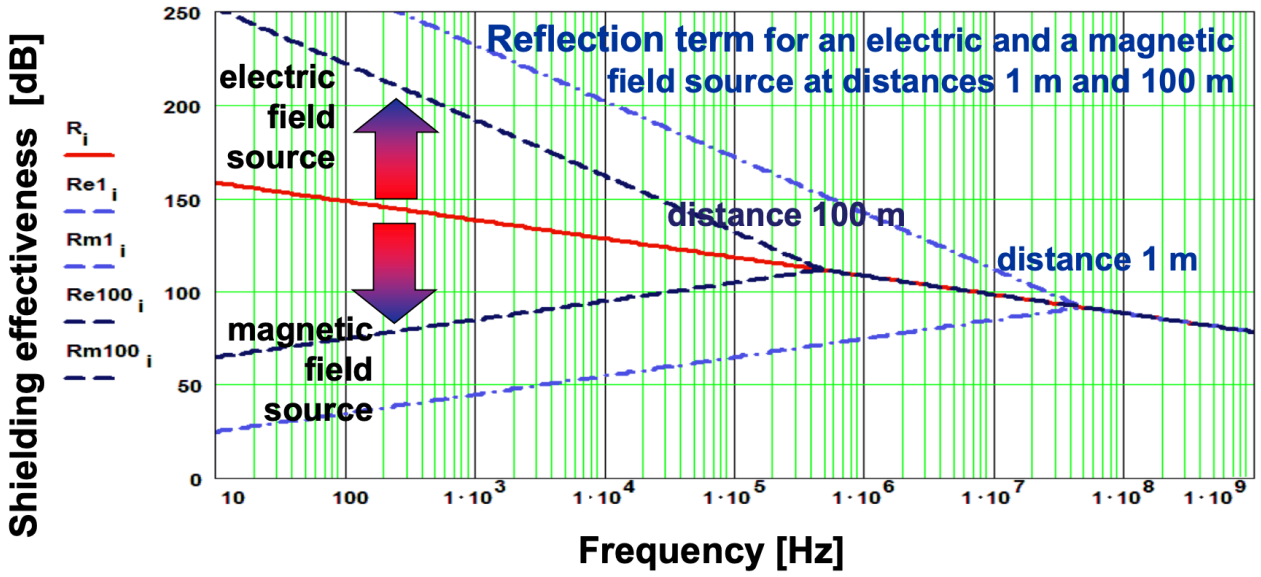
Valid when $\hat{Z}_w \gg \hat{\eta}$.
This condition may not hold for low-frequency magnetic sources.

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)

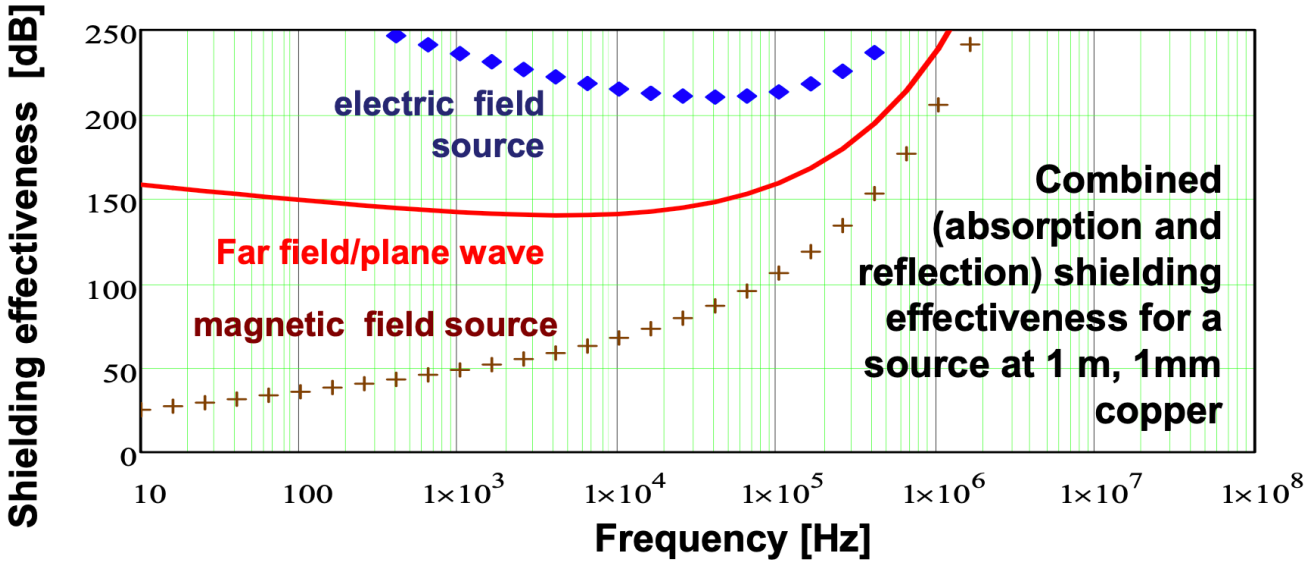
$$R_{\text{dB}} = 168 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f}\right)$$

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

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

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

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

