Shielding

Introduction

Concept of shielding

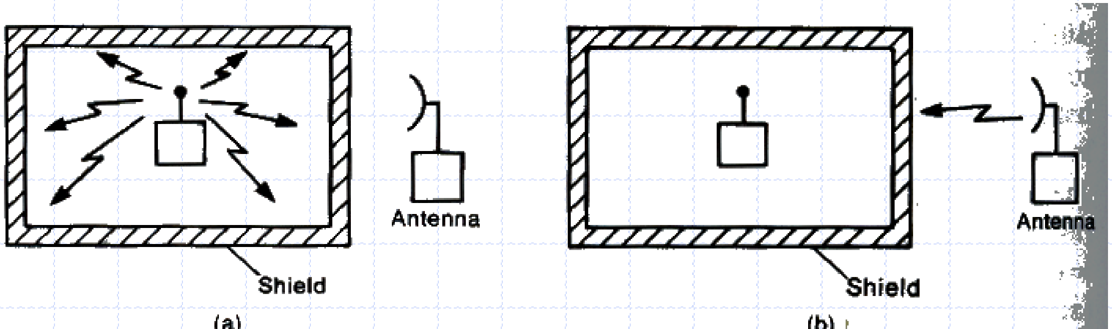


FIGURE 11.1 Illustration of the use of a shielded enclosure: (a) to contain radiated emissions and (b) to exclude radiated emissions.

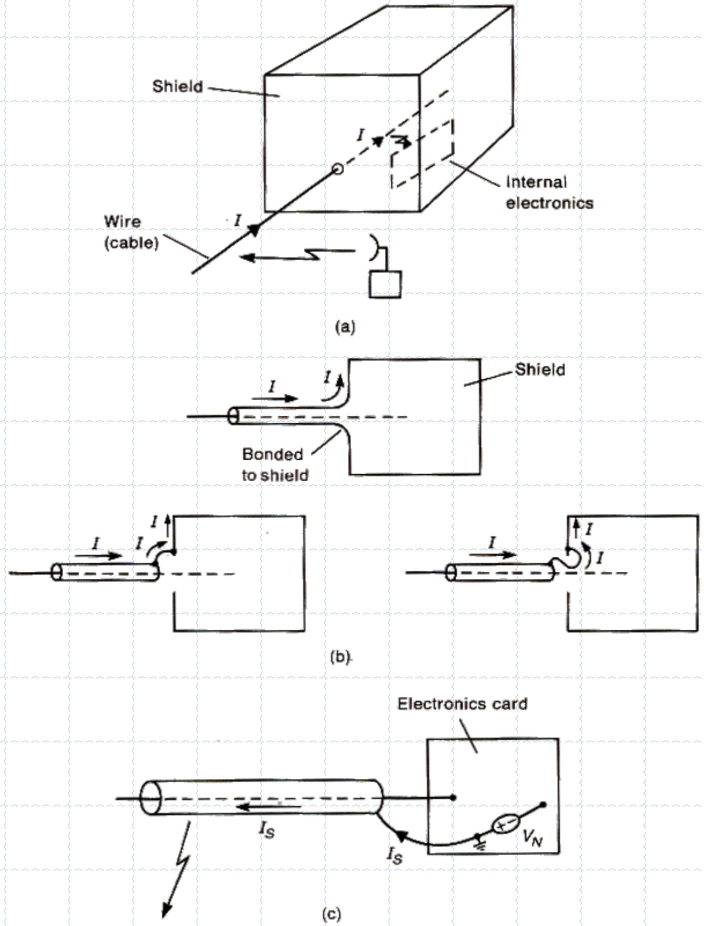


FIGURE 11.2 Important practical considerations that seriously degrade shielding effectiveness: (a) penetration of an enclosure by a cable allowing direct entry of external fields; (b) pigtail termination of a cable shield at the entry point to a shielded enclosure; (c) termination of a cable shield to a noisy point causing the shield to radiate.

Shielding of a metal shield (theory)

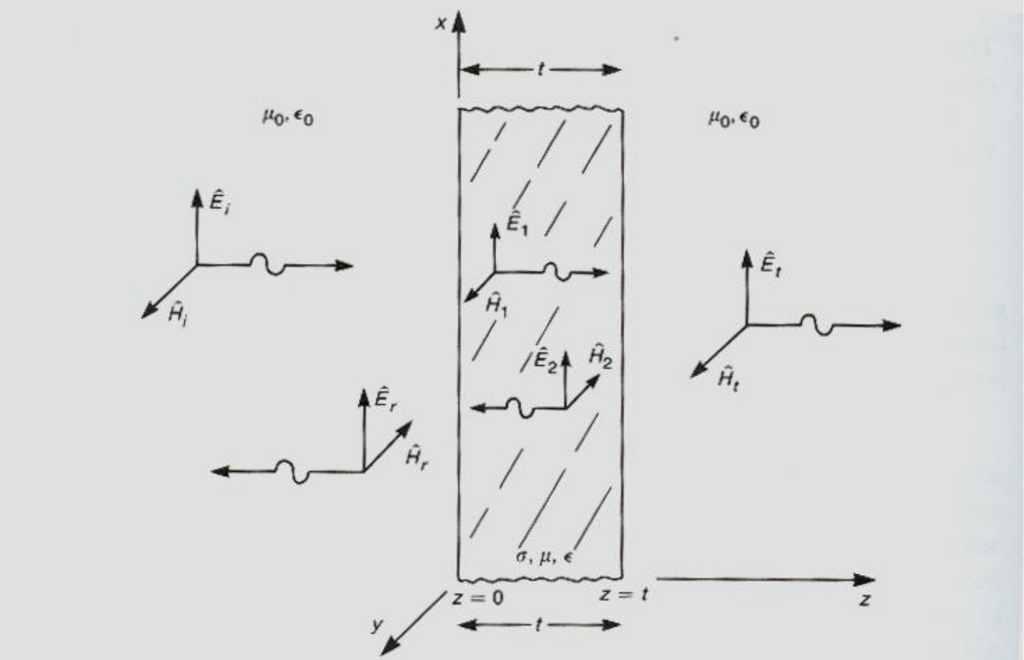


FIGURE 11.4 Illustration of the shielding effectiveness of a conducting barrier to a normal-incidence uniform plane wave.

For E field

$$S.E. = 20\log\frac{|E_i|}{|E_t|}$$

For H field

$$S.E. = 20\log\frac{|H_i|}{|H_t|}$$

Do they be equal ?

Shielding of a metal shield (theory)

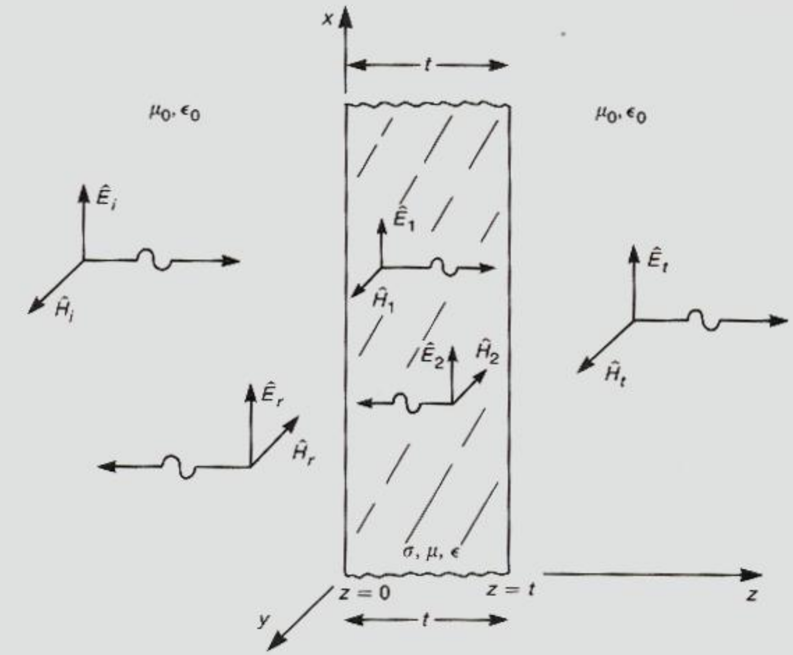


FIGURE 11.4 Illustration of the shielding effectiveness of a conducting barrier to a normal-incidence uniform plane wave.

It depends.

For plane wave, they are equal
But for near field, they are not.

Shielding of a metal shield (theory)

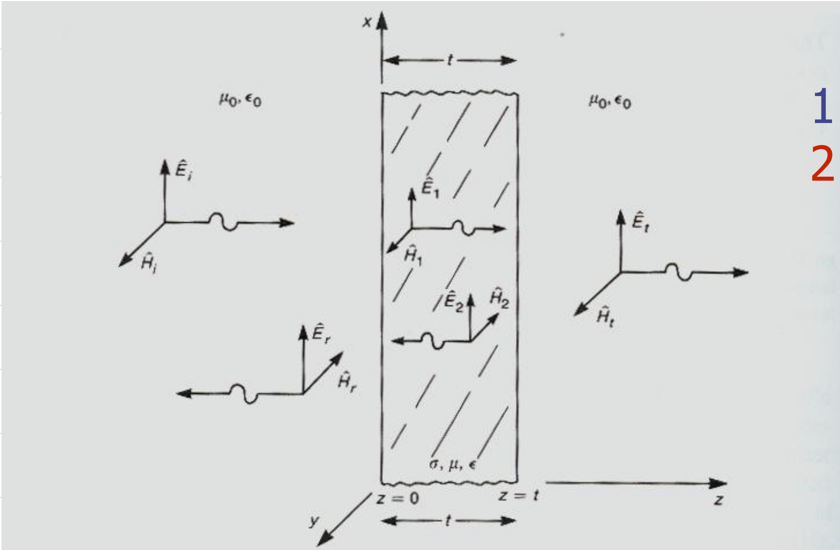


FIGURE 11.4 Illustration of the shielding effectiveness of a conducting barrier to a normal-incidence uniform plane wave.

1. Plane wave assumption
2. Continuity of E and H at each boundary

$$\frac{E_i}{E_t}=\frac{(\eta_0+\eta)^2}{4\eta_0\eta}[1-(\frac{\eta_0-\eta}{\eta_0+\eta})e^{-2t/\delta}e^{-j2\beta t}]e^{t/\delta}e^{j\beta t}e^{-j\beta_0 t}$$

How to derive?

where $\eta=\sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}}$ δ : Skin depth

11.1 Shielding effectiveness. (S.E.)

a. Definition

$$(1)\ \textit{for electric firld}:\quad S.E. = 20\cdot\log\left|\frac{\hat{E}i}{\hat{E}_t}\right|$$

$$(2)\ \textit{for magnetic field}:\quad S.E. = 20\cdot\log\left|\frac{\hat{H}i}{\hat{H}_t}\right|$$

note:

1. If the incident field is an uniform plane wave,and the medium on each side of the barrier are identical, (1) and (2) definitions are identical.

2. For near fields and/or different medium, (1) and (2) are not equivalent.

3. Definition (1) (for Ê field) is taken as standard for 2 case.

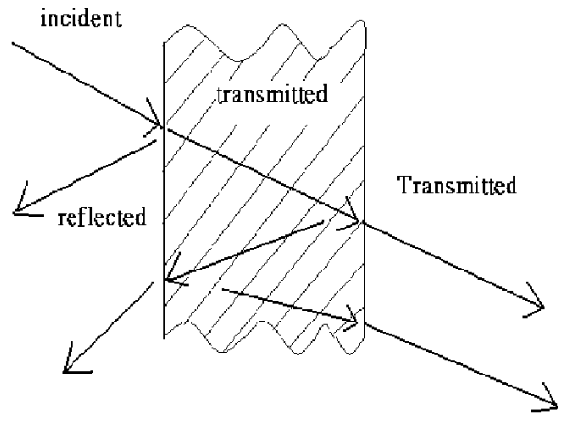
$C.$ *Causes of shield*

(1) Reflection.

(2) Absorption: $e^{-\alpha z}$ (α : attenuation)

$$\alpha \propto \frac{1}{\delta}$$

(3) Multiple reflection



Note: (1) & (2) will increase the S.E. of the barrier, but (3) will decrease the S.E. of barrier.

$$S.E._{dB} = R_{dB} + A_{dB} + M_{dB}$$

11.2 Shielding effectiveness: far field sources

11.2.1. *Exact solution*

(1) *For plane wave* :

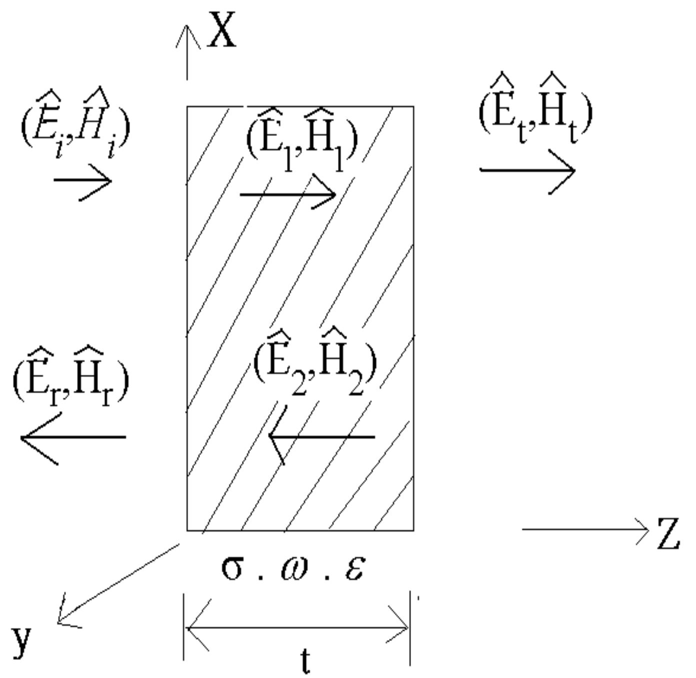
$$\vec{E}_i = \hat{E}_i \, e^{-j\beta_0 z} \, \hat{a}_x$$

$$\vec{H}_i = \hat{E}_i / \eta_0 \times e^{-j\beta_0 z} \, \hat{a}_y$$

$$\vec{E}_r = \hat{E}_r \, e^{-j\beta_0 z} \, \hat{a}_x$$

$$\vec{H}_r = -\hat{E}_r / \eta_0 \times e^{-j\beta_0 z} \, \hat{a}_y$$

$$\vec{E}_1 = \hat{E}_1 \, e^{-\gamma z} \, \hat{a}_x$$



$$\overline{H}_1 = \hat{E}_1 / \eta_0 \times e^{-\gamma z} \ \hat{a}_y$$

$$\overline{E}_2 = \hat{E}_2 \ e^{-\gamma z} \ \hat{a}_x$$

$$\overline{H}_2 = -\hat{E}_2 / \eta_0 \times e^{-\gamma z} \ \hat{a}_y$$

$$\overline{E}_t = \hat{E}_t \ e^{-j\beta_0 z} \ \hat{a}_x$$

$$\overline{H}_t = \hat{E}_t / \eta_0 \times e^{-j\beta_0 z} \ \hat{a}_y$$

where

$$\beta_0 = \omega_0 \sqrt{\mu_0 \varepsilon_0}$$

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

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

$$\hat{\eta} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} = \eta \angle \theta_\eta$$

Exact solution

(2) $\hat{E}_i$ *is known, and to determine the remaining amplitudes.*

$\hat{E}_r, \hat{E}_1, \hat{E}_2$, *and* $\hat{E}_t$.

$$B.C. \Rightarrow \ at\ Z=0 \quad \vec{E}_i + \vec{E}_r = \vec{E}_1 + \vec{E}_2 \qquad \vec{E}_i + \vec{E}_r = \vec{E}_1 + \vec{E}_2$$

$$\vec{H}_i + \vec{H}_r = \vec{H}_1 + \vec{H}_2 \qquad \frac{\vec{E}_i}{\eta_0} + \frac{\vec{E}_r}{\eta_0} = \frac{\vec{E}_1}{\eta_0} + \frac{\vec{E}_2}{\eta_0}$$

$$at\ Z=t \quad \vec{E}_1 + \vec{E}_2 = \vec{E}_t \qquad \vec{E}_1 e^{-\hat{\gamma} t} + \vec{E}_2 e^{-\hat{\gamma} t} = \vec{E}_t e^{-\hat{\gamma} t}$$

$$\vec{H}_1 + \vec{H}_2 = \vec{H}_t \qquad \frac{\vec{E}_1}{\eta_0} e^{-\hat{\gamma} t} - \frac{\vec{E}_2}{\eta_0} e^{-\hat{\gamma} t} = \frac{\vec{E}_t}{\eta_0} e^{-\hat{\gamma} t}$$

$$(3).\ \therefore \frac{\left(\eta_0 + \hat{\eta}\right)^2}{4\eta_0 \hat{\eta}} \left[1 - \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)^2 e^{-2t/\delta} e^{-j2\beta t} \right] e^{t/\delta} e^{j\beta t} e^{-j\beta_0 t}$$

$\Leftarrow$ *exact solution. where* $\delta = 1/\alpha,\ \alpha + j\beta = \hat{\gamma}$ *in barrier metal.*

(4) Simplifications:

1. assume the barrier is a "good conductor".

$$\therefore \hat{\eta} \ll \eta_0 \Rightarrow \frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}} \cong 1.$$

2. skin depth δ << barrier thickness t.

$$\therefore e^{-\gamma t} = e^{-\alpha t} \cdot e^{-j\beta t} = e^{-t/\delta}\, e^{-j\beta t} \ll 1$$

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

(5) $\therefore S.E_{dB} \cong 20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right| + 20\log_{10} e^{t/\delta} + M_{dB}.$

$P.S.:\quad 20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right| : R_{dB},\ 20\log_{10} e^{t/\delta} : A_{dB}.$

(6) The Multiple - reflection term is the middle term of (3).

$$M_{dB} = 20\log\left|1-\left(\frac{\hat{\eta}_0-\hat{\eta}}{\hat{\eta}_0+\hat{\eta}}\right)^2 e^{-2t/\delta} e^{-j2\beta t}\right|$$

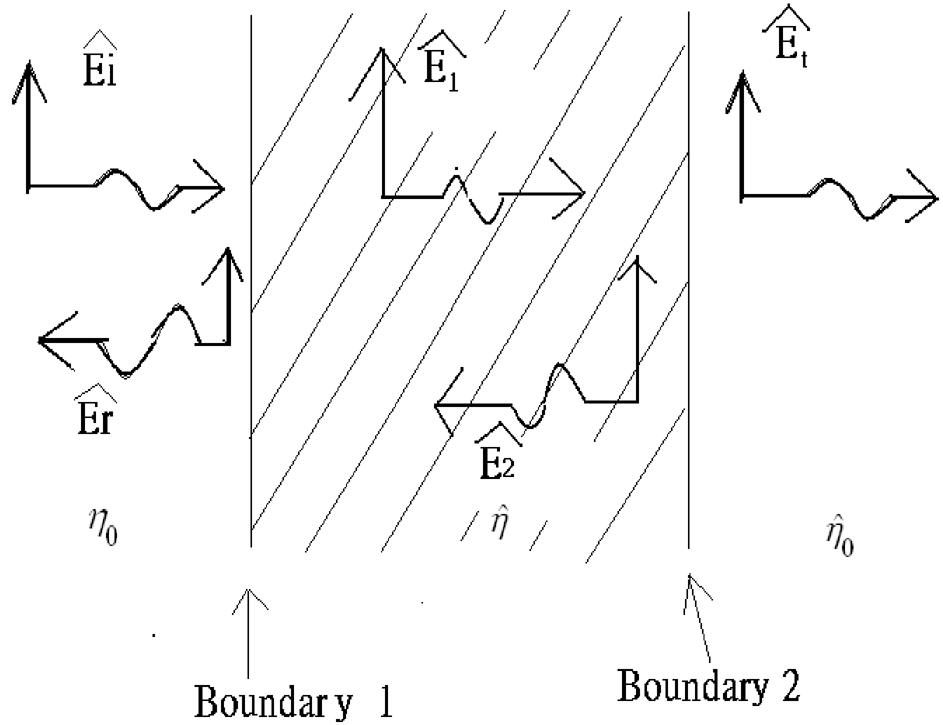
$$\cong 20\log\left|1-e^{-2t/\delta}e^{-j2t/\delta}\right| \cong 0 \quad (\Leftarrow if\ t \gg \delta)$$

$$where\ \alpha = \beta = \frac{1}{\delta}\ for\ good\ conductor.$$

11.2.2 Approximate solution

$Assumption:$ (1) $\hat{\eta} << \eta_0$ (*a good conductor*)

(2) $t >> \delta$



$a.$ Reflection Loss ($\vec{E}$ *field*)

$\because t >> \delta$

$\therefore \vec{E}_2 \to 0.$

$$(1) \quad \frac{\hat{E}_1}{\hat{E}_i} \cong \frac{2\hat{\eta}}{\eta_0 + \hat{\eta}}$$

$$(2) \quad \frac{\hat{E}_t}{\hat{E}_1} \cong \frac{2\eta_0}{\eta_0 + \hat{\eta}}$$

(3) *In the absence of attenuation*

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

the same as exact solution.

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

$$\hat{\eta} << \eta_0$$

Note: The transimission coefficient is very small $\left(\frac{2\hat{\eta}}{\hat{\eta} + \eta_0} \to 0 \right)$ *at the Boundary* 1, *and is approximately* 2 *at the Boundary* 2.

$\therefore$ *very little of* $\vec{E}$ *field is transmitted through the* B.1.

$$(1)\quad \frac{\hat{H}_1}{\hat{H}_i} = \frac{\hat{E}_1 / \hat{\eta}}{\hat{E}_i / \eta_0} = \frac{\hat{E}_1}{\hat{E}_i} \cdot \frac{\eta_0}{\hat{\eta}} = \frac{2\eta_0}{\eta_0 + \hat{\eta}} \rightarrow 2$$

$$\text{if} \quad \hat{\eta} \ll \eta_0$$

$$(2)\quad \frac{\hat{H}_t}{\hat{H}_1} = \frac{\hat{E}_t / \eta_0}{\hat{E}_1 / \hat{\eta}} = \frac{\hat{E}_t}{\hat{E}_1} \cdot \frac{\hat{\eta}}{\eta_0} = \frac{2\hat{\eta}}{\eta_0 + \hat{\eta}} \rightarrow 0$$

$$\text{if} \quad \hat{\eta} \ll \eta_0$$

$$(3)\quad \frac{\hat{H}_t}{\hat{H}_i} = \frac{\hat{H}_t}{\hat{H}_i} \cdot \frac{\hat{H}_t}{\hat{H}_i} = \frac{4\eta_0 \hat{\eta}}{\left(\hat{\eta} + \eta_0\right)^2}$$

Note:

$$1.\ \frac{\hat{E}_t}{\hat{E}_i} = \frac{\hat{H}_t}{\hat{H}_i} = \frac{4\eta_0\hat{\eta}}{(\eta_0+\hat{\eta})^2}$$

2. But primary transmission of $\vec{\mathrm{H}}$ field occurs at the boundary 1,whereas the primary transmission of the $\vec{\mathrm{E}}$ field occurs at the boundary 2.

3. It means that "thick" boundary has more effect on shielding against $\vec{\mathrm{H}}$ field than to the $\vec{\mathrm{E}}$ field.

C. Absorption loss

$\vec{E}_1$ is attenuated in the conductor.

$\therefore$ Absorption factor

$$A = e^{t/\delta} \Rightarrow A_{dB} = 20\log e^{t/\delta}$$

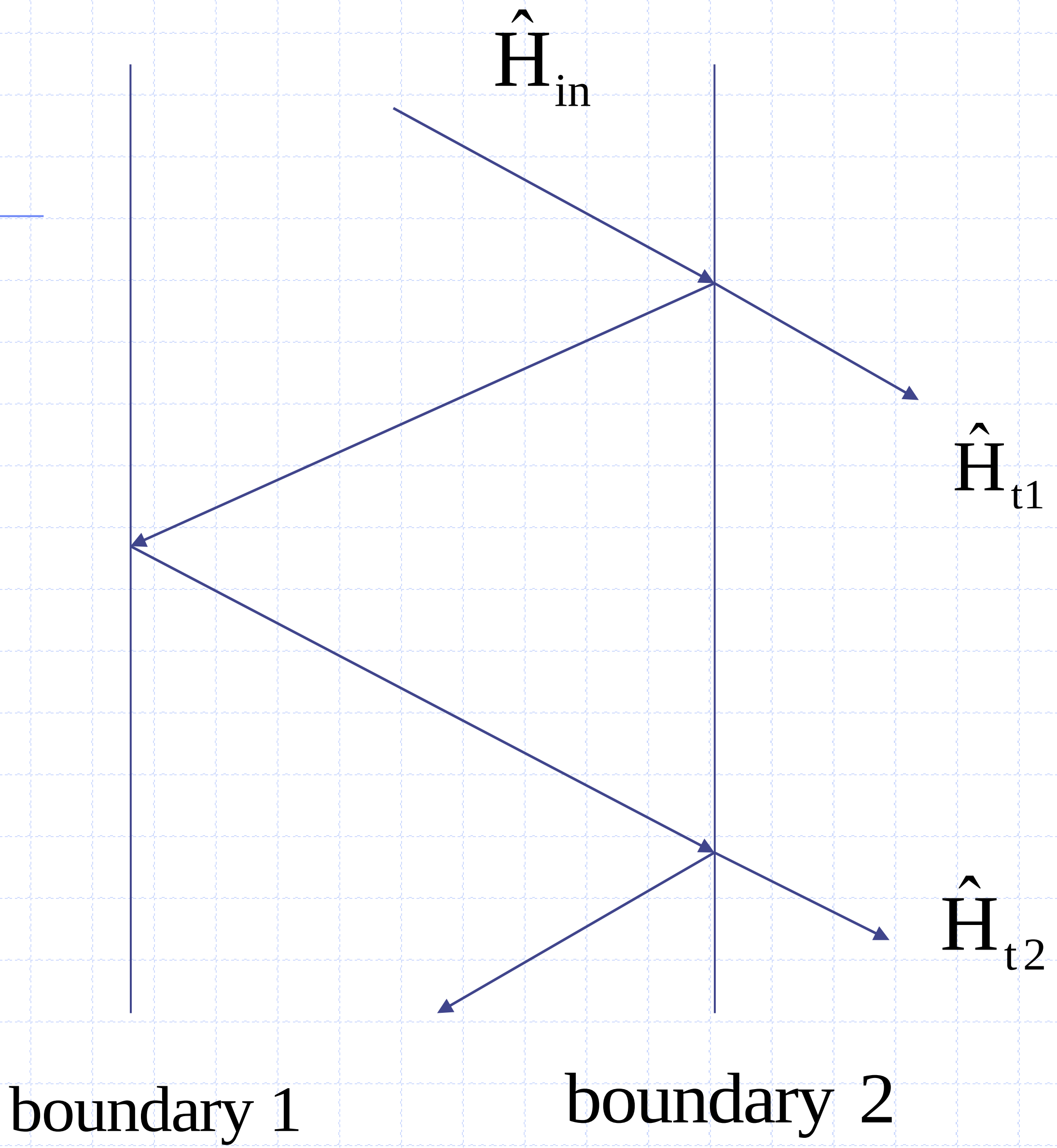
d. Multiple Reflection Loss

- When t >>δ the multiple reflection loss may be important.
- (1) for magnetic field

    1.

$$\hat{H}_{t1} = \hat{T}_H \cdot \hat{H}_{in} = \frac{\hat{\eta}}{\eta_0}\hat{T}_E \cdot \hat{H}_{in}$$

$$= \left(\frac{2\hat{\eta}}{\hat{\eta}+\eta_0}\right)\hat{H}_{in}$$


$\hat{H}_{in}$
$\hat{H}_{t1}$
$\hat{H}_{t2}$
boundary 1
boundary 2

2. The reflected wave is

$$-\Gamma_E e^{-rt}\hat{H}_{in} \leftarrow at\ boundary\ 1$$

$$= -\left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right) e^{-rt}\hat{H}_{in}$$

$$\Gamma_E{}^2 e^{-2rt}\hat{H}_{in} \leftarrow at\ boundary\ 2$$

3.

$$\hat{H}_{t2} = \hat{T}_H \cdot \Gamma_E{}^2 e^{-2rt}\hat{H}_{in}$$

4.

$$\therefore \hat{H}_t = \hat{H}_{t1} + \hat{H}_{t2} + \hat{H}_{t3} + \cdots$$

$$= \hat{H}_{t1}\left(1 + \left(\Gamma_E e^{-rt}\right)^2 + \left(\Gamma_E e^{-rt}\right)^4 + \cdots\right) \quad let\ \left(\Gamma_E e^{-rt}\right) = \Delta$$

$$= \hat{H}_{t1} \Big/ (1-\Delta^2) \quad , \ (\Delta < 1)$$

5.

$$(SE)_{dB} = -20\log\left|\frac{\hat{H}_t}{\hat{H}_i}\right| = -20\log\left|\frac{\hat{H}_{t1}}{\hat{H}_i}\right| - 20\log\left|1+\Delta^2+\Delta^4+\cdots\right|$$

6.

$$M_{dB} = 20\log\left|1-\left(\frac{\eta_0-\hat{\eta}}{\eta_0+\hat{\eta}}\right)^2 e^{-2\gamma t}\right|$$

$$\cong 20\log\left|1-\left(\frac{\eta_0-\hat{\eta}}{\eta_0+\hat{\eta}}\right)^2 e^{-2t/\varsigma}\cdot e^{-j2t\beta}\right|$$

same as exact solution

§11.3 Shielding effectiveness - near field sources

a. In the far field:

$$(1) E_\theta \ and \ H_\phi \ are \ orthogonal$$

$$(2) E_\theta / H_\phi = \eta_0$$

$$(3) d > 3\lambda_0$$

b. Near field for Hertzian dipole

(1)

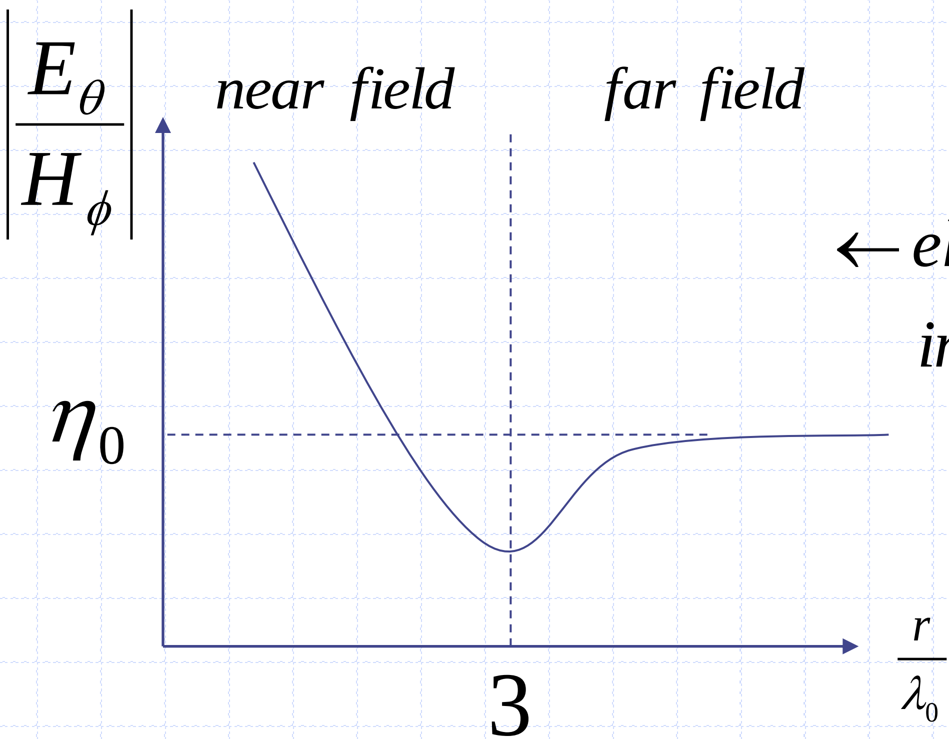
$$\hat{Z}_w = \frac{\hat{E}_\theta}{\hat{H}_\phi} = \eta_0 \frac{\frac{j}{\beta_0 r} + \frac{j}{(\beta_0 r)^2} - \frac{j}{(\beta_0 r)^3}}{\frac{j}{\beta_0 r} + \frac{1}{(\beta_0 r)^2}}$$

$$\cong \eta_0 \frac{-\frac{j}{(\beta_0 r)^3}}{\frac{1}{(\beta_0 r)^2}} = \frac{\eta_0}{\beta_0 r} \angle -90^\circ$$

(2)

$$\left|\hat{Z}_w\right|_e = \frac{\eta_0}{\left(\frac{2\pi}{\lambda_0}\right) r} = 60\frac{\lambda_0}{r}$$

(3)



$\leftarrow$ *electric dipole is a high impedance source*

- c. Near field for magnetic dipole (loop)

(1)

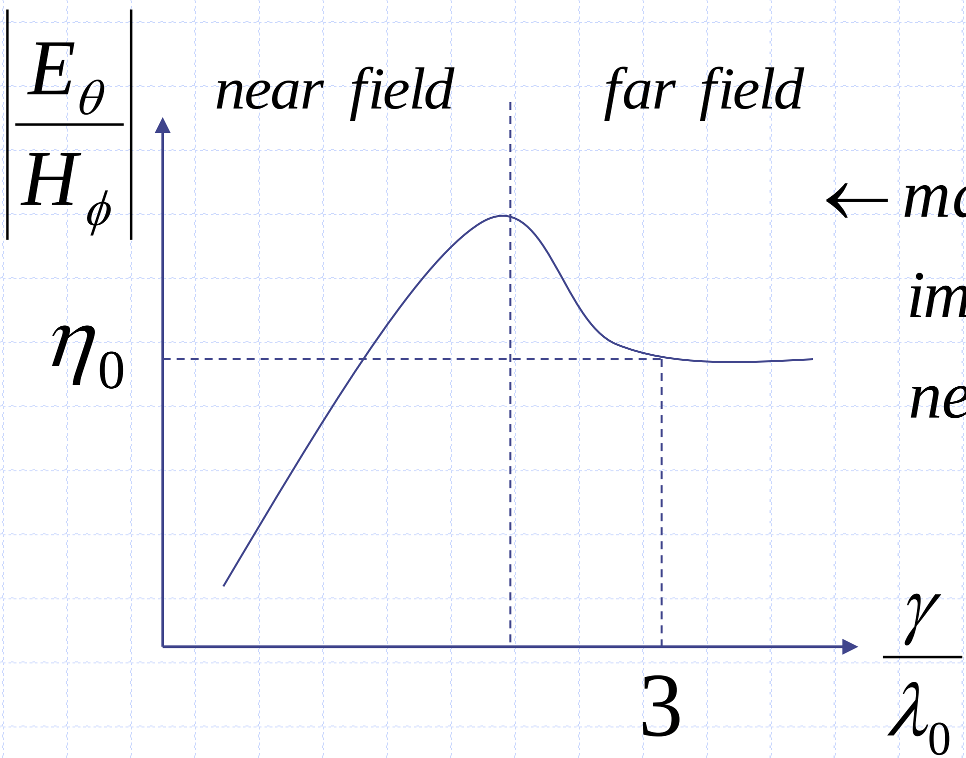
$$\hat{Z}_w = \frac{\hat{E}_\phi}{\hat{H}_\theta} = -\eta_0 \frac{j/\beta_0 r + 1/(\beta_0 r)^2}{1/\beta_0 r + 1/(\beta_0 r)^2 - j/(\beta_0 r)^3}$$

$$= \eta_0 \beta_0 r \angle -90^\circ$$

(2)

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

(3)



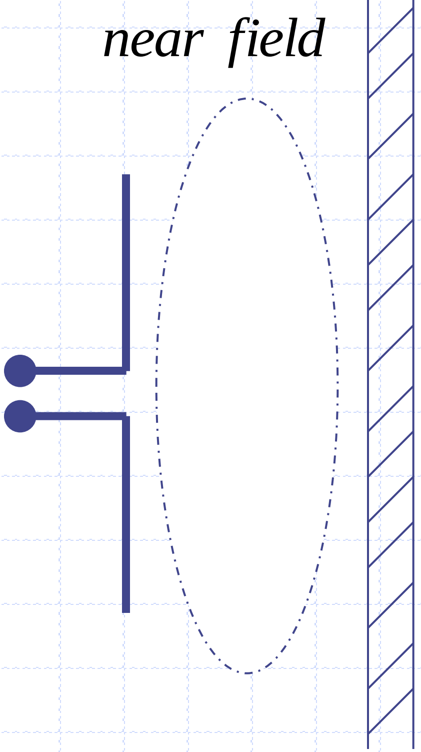
← *magnetic dipole is a low impedance source in the near field*

d. Reflection loss for Electric source

(1) we know for plane wave

$$R_{dB} = 20\log\left|\frac{\hat{E}_i}{\hat{E}_t}\right|$$

(2) $$= 20\log\left|\frac{(\eta_0+\hat{\eta})^2}{4\eta_0\hat{\eta}}\right| \cong 20\log\left|\frac{\eta_0}{4\hat{\eta}}\right|$$



$$\text{using} \quad \hat{Z}_w \cong -j\frac{\eta_0}{\beta_0 r} \rightarrow \eta_0$$

$$\therefore R_{dB} \cong 20\log\left|\frac{\hat{Z}_w}{4\hat{\eta}}\right| \cong 322 + 10\log\left(\frac{\sigma_r}{\mu_r f^3 r^2}\right)$$

Shielding of a metal shield (Near Field)

Electric dipole

Magnetic dipole

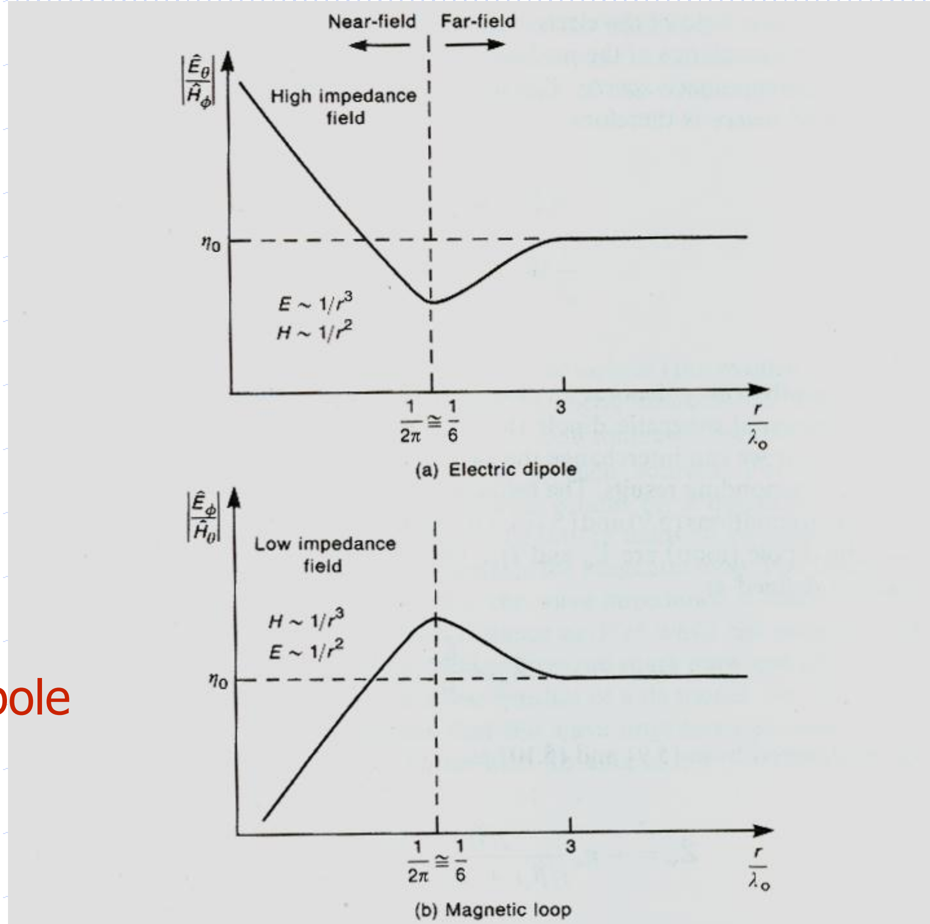


FIGURE 11.10 Wave impedance of (a) the electric (Hertzian) dipole and (b) the magnetic (loop) dipole.

$$Z_w = 60\frac{\lambda_0}{r}$$

$$Z_w = 2369\frac{r}{\lambda_0}$$

Shielding of a metal shield (Near Field)

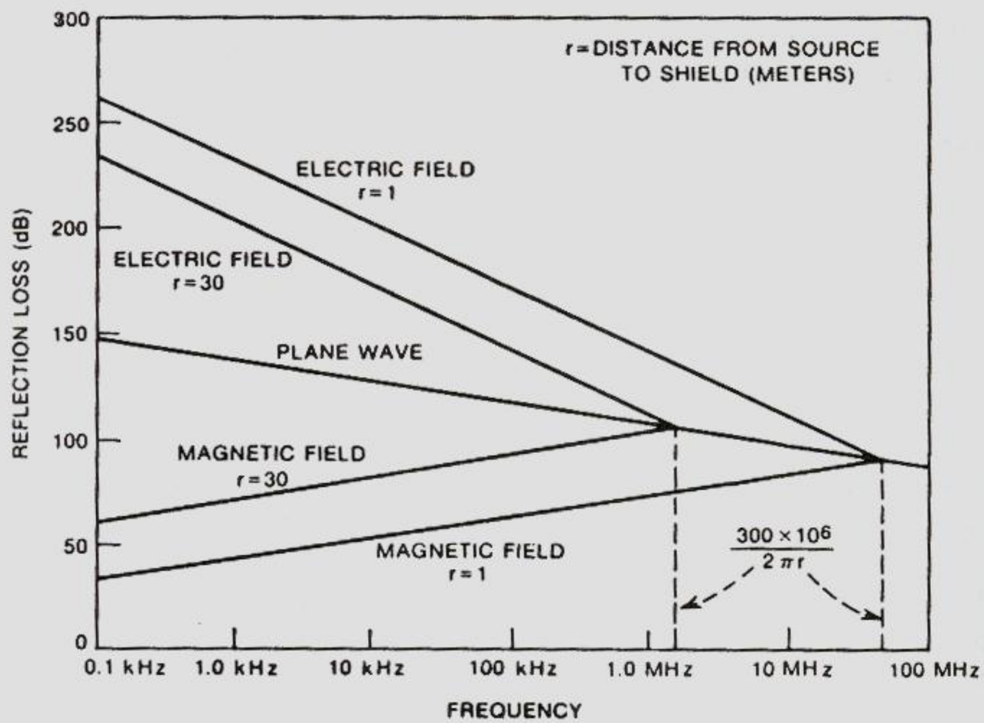


FIGURE 11.11 Reflection loss of near-field electric and magnetic sources [3].

For electric dipole

$$R_e = 322 + 10\log\left(\frac{\sigma_r}{\mu_r f^3 r^2}\right)$$

For magnetic dipole

$$R_m = 14.57 + 10\log\left(\frac{f r^2 \sigma_r}{\mu_r}\right)$$

Shielding of a metal shield (Near Field)

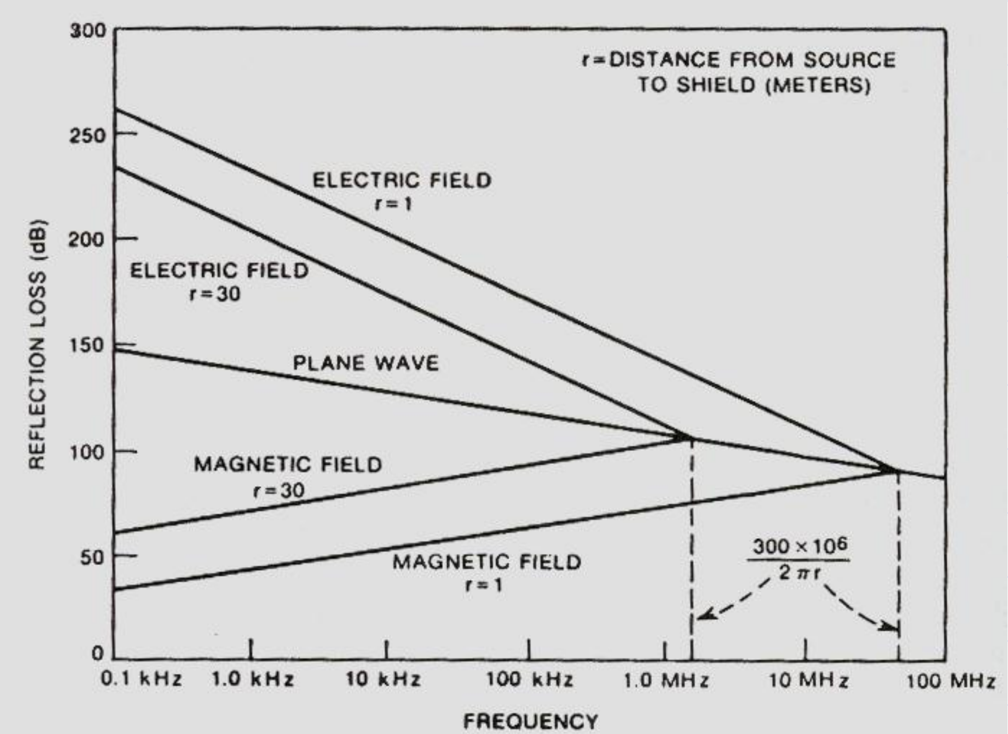


FIGURE 11.11 Reflection loss of near-field electric and magnetic sources [3].

1. Reflection Loss increase as frequency decrease for E field
2. Reflection Loss decrease as frequency decrease for H field

Note: The Absorption loss also Decrease as frequency decrease for H-field.

How to solve the SE of magnetic field?

An example of S.E. for copper plate

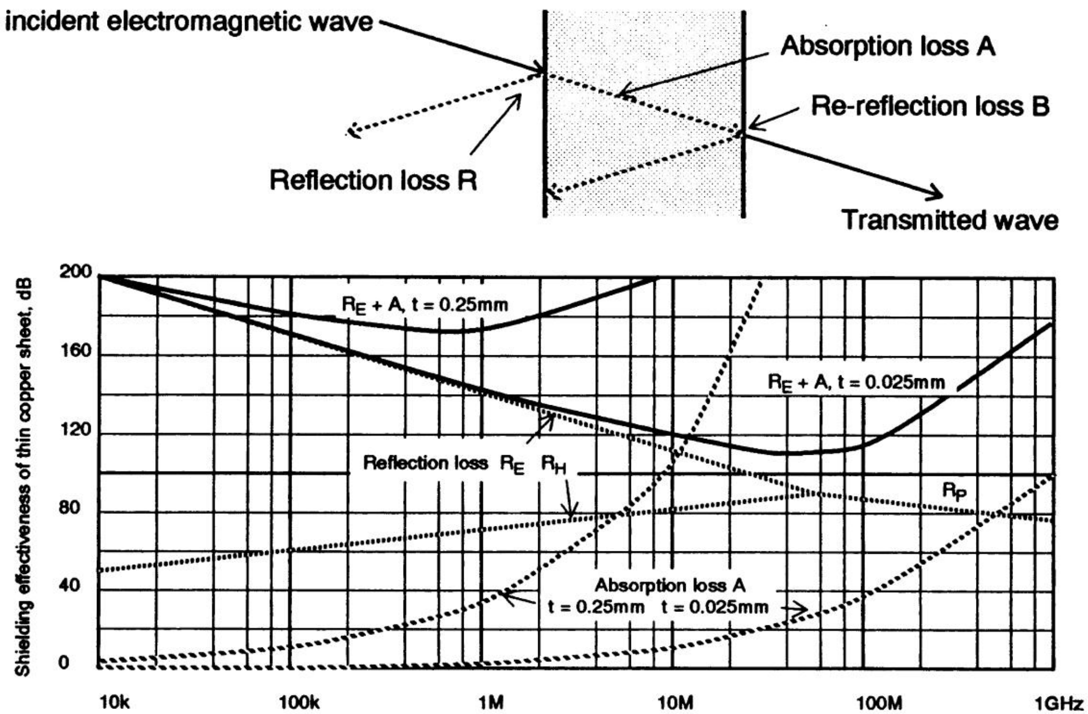


Figure 7.33 Shielding effectiveness versus frequency for copper sheet

Low Frequency, Magnetic Shielding

Two approaches

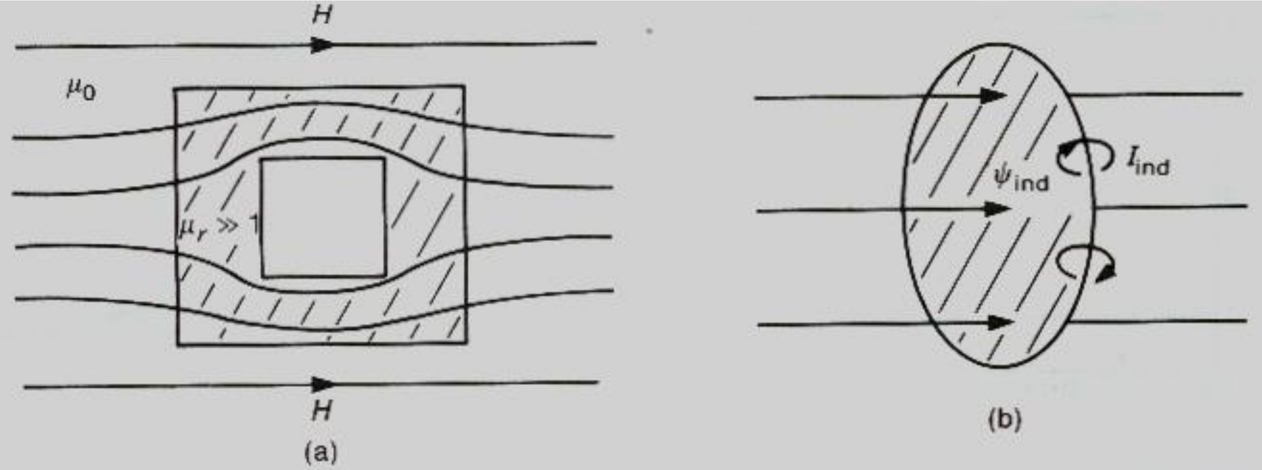


FIGURE 11.12 Two important methods of shielding against low-frequency magnetic fields: (a) using a highly permeable ferromagnetic material to divert the magnetic field; (b) using "bands" to generate an opposing magnetic field.

Low Frequency, Magnetic Shielding

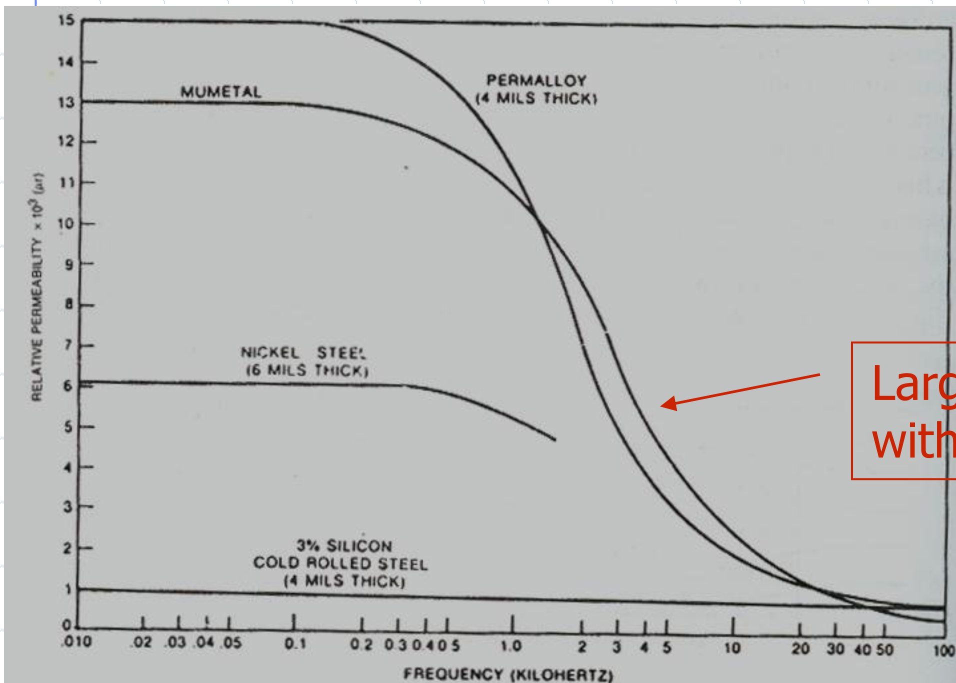


FIGURE 11.13 Illustration of the frequency dependence of various ferromagnetic materials [3].

Two factors that may degrade the ferromagnetic material:

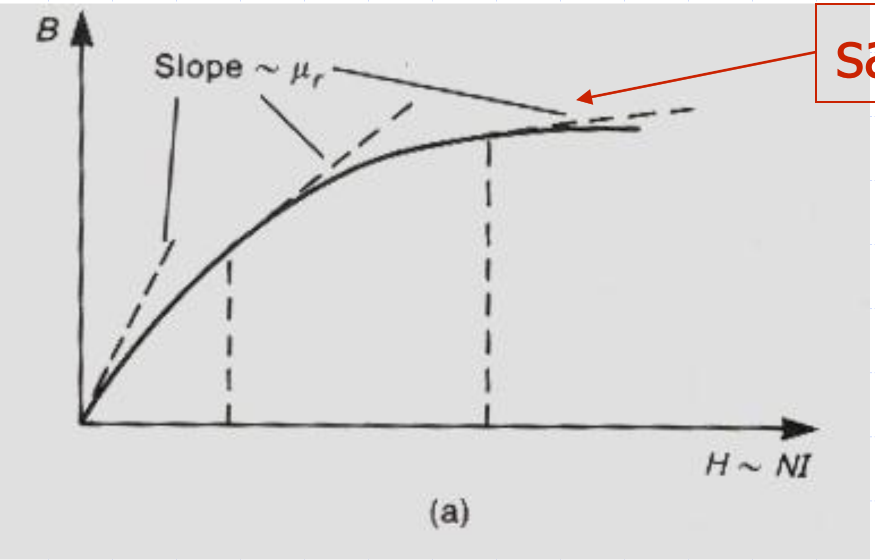
1. Increasing frequency.
2. Increasing the field strength.

Larger than 4KHz, the u is the same with the steel

That's why we use the steel as
The magnetic shielding material for
Switch-mode Power Supply (20-100KHz

Low Frequency, Magnetic Shielding

Phenomenon of the saturation of ferromagnetic materials

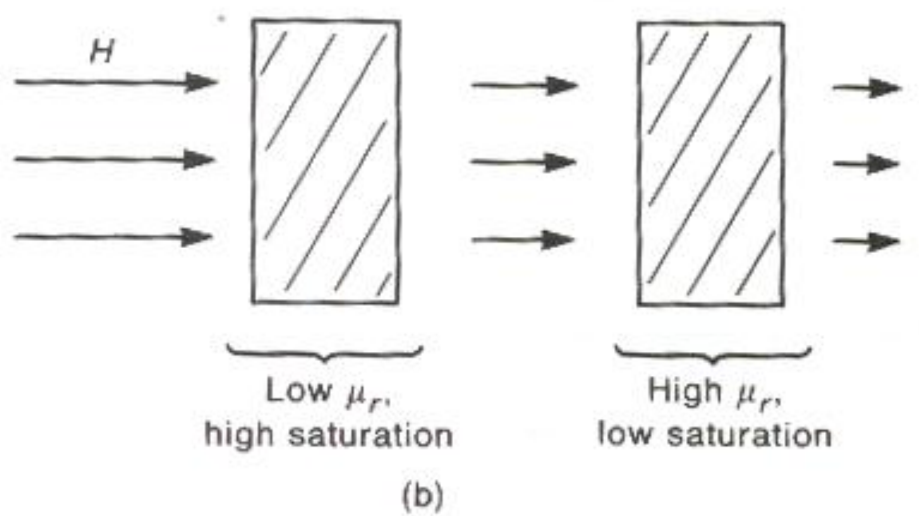


saturation

When increase the H-field

Low Frequency, Magnetic Shielding

Solution: Using multi-layer to reduce the effect of the saturation



The effect of aperture

In practice, the S.E. is limited by the necessary apertures and discontinuities.

The simplest formula

$$SE = 20\log\frac{\lambda}{2d}$$

The modified formula

Ex: 20dB SE for 1GHz
then, d < 1.6cm

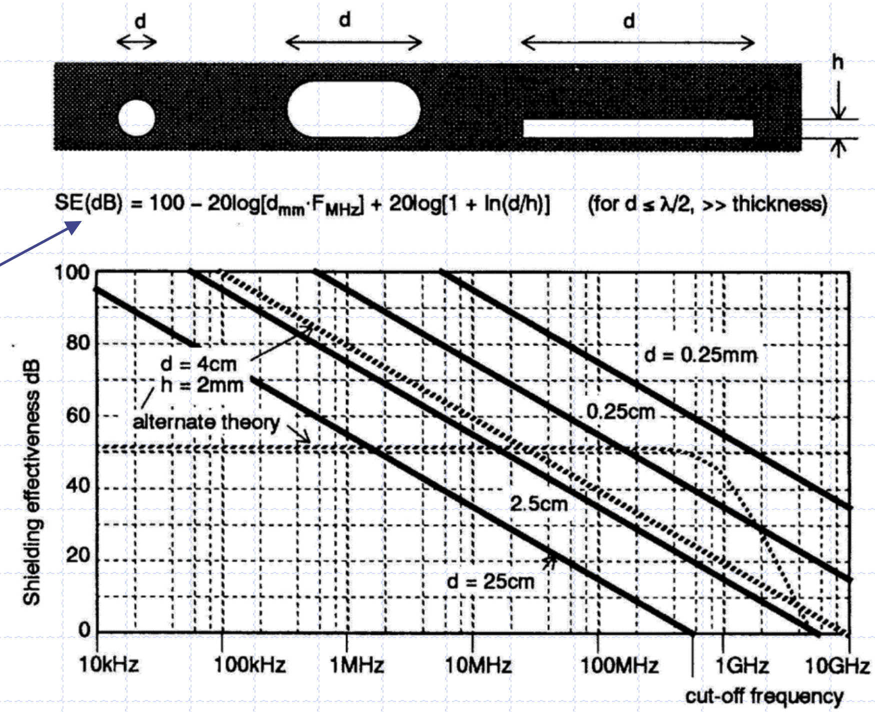


Figure 7.34 Shielding effectiveness degradation due to apertures

The effect of mesh and Honeycomb

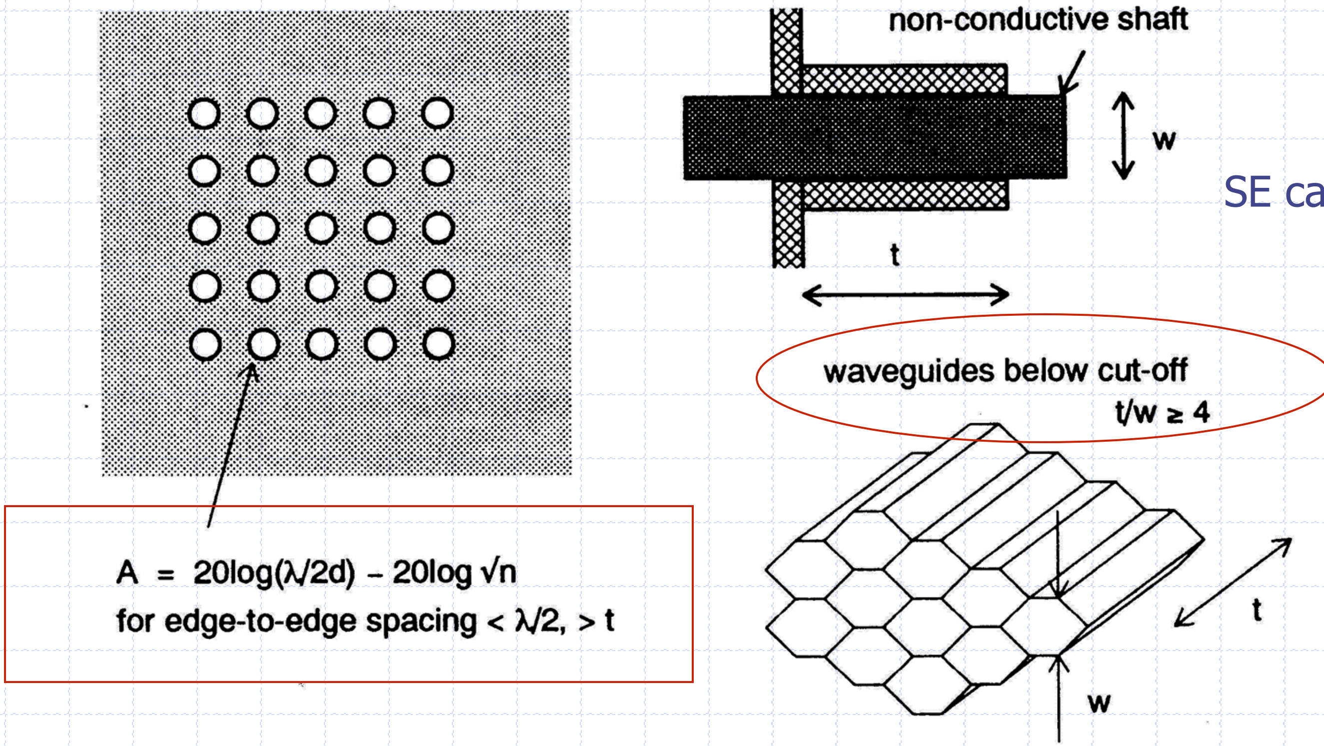


Figure 7.37 Mesh panels and the waveguide below cut-off

SE can reach 100dB

Why ?

The effect of Seams

Poor

Better

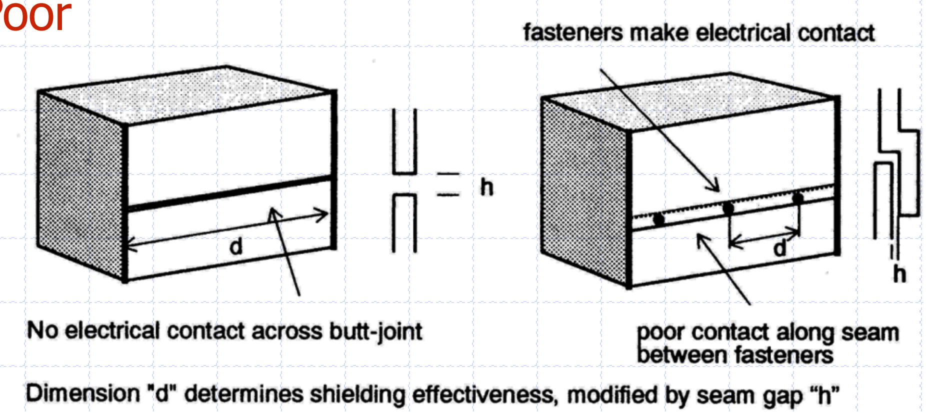


Figure 7.38 Seams between enclosure panels

Best

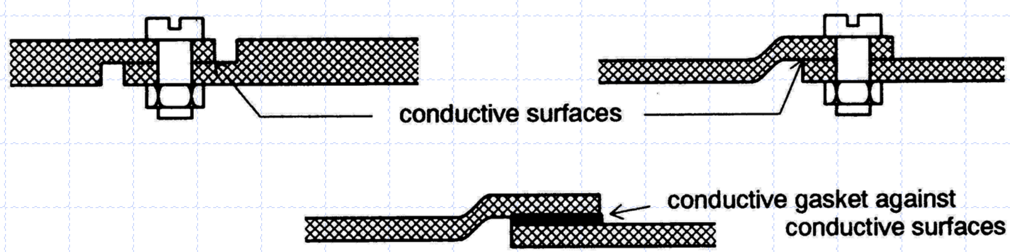


Figure 7.39 Cross sections of joints for good conductivity

The effect of aperture orientation

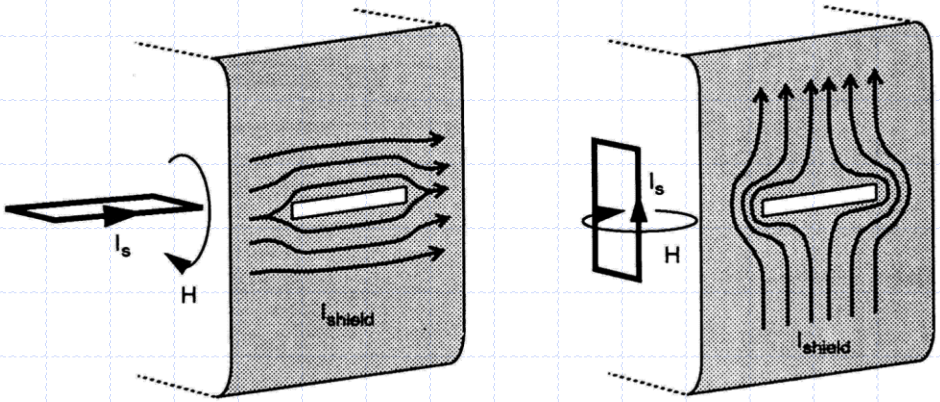


Figure 7.40 Current loop versus aperture orientation

Which one is better?

By this trick, the SE can be improved up to 10dB

The effect of image plane

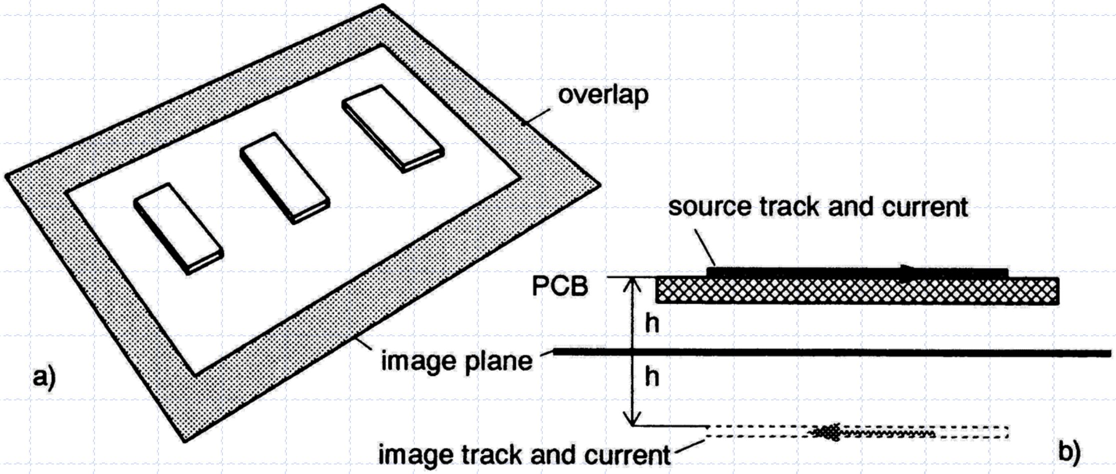


Figure 7.41 Image plane under a PCB

Enclosure resonance

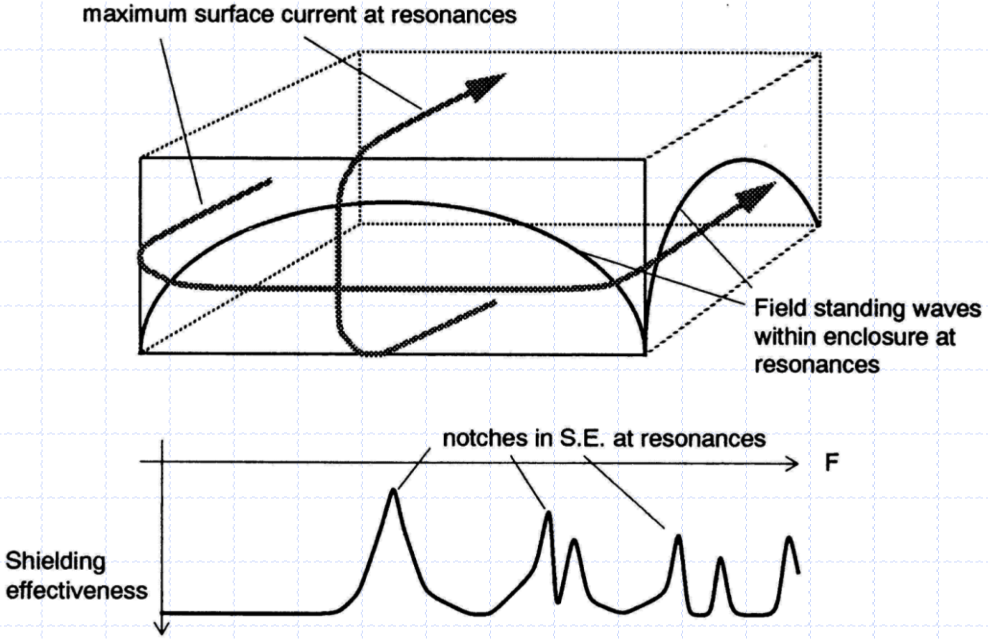


Figure 7.42 Resonances degrade shielding effectiveness

$$F = 150\sqrt{(k/l)^2 + (m/h)^2 + (n/w)^2} \quad \text{MHz}$$

F ~ 212/l ~ 212/h ~ 212/w for equal square enclosure

Gasket and Contact Strip

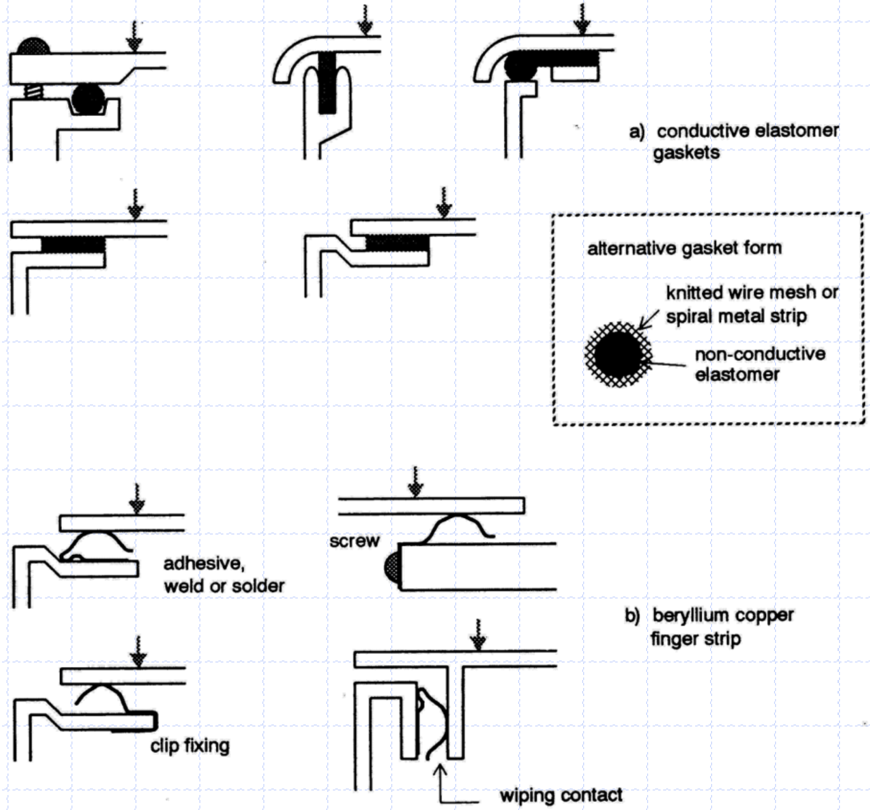


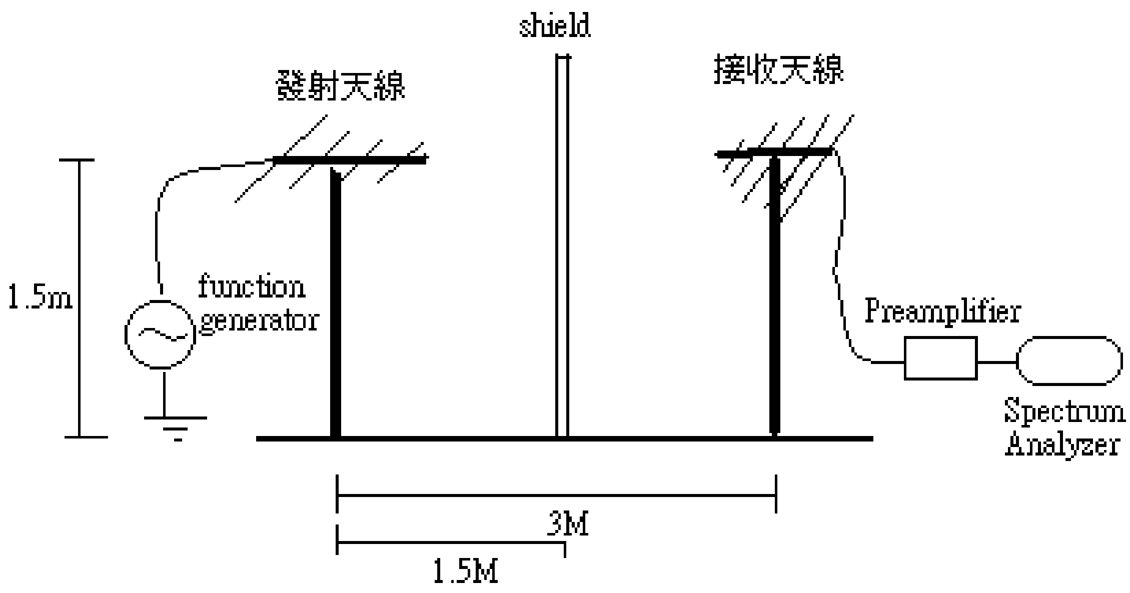
Figure 7.43 Usage of gaskets and finger strip

Choosing concern:

1. Conductivity
2. Ease of mounting

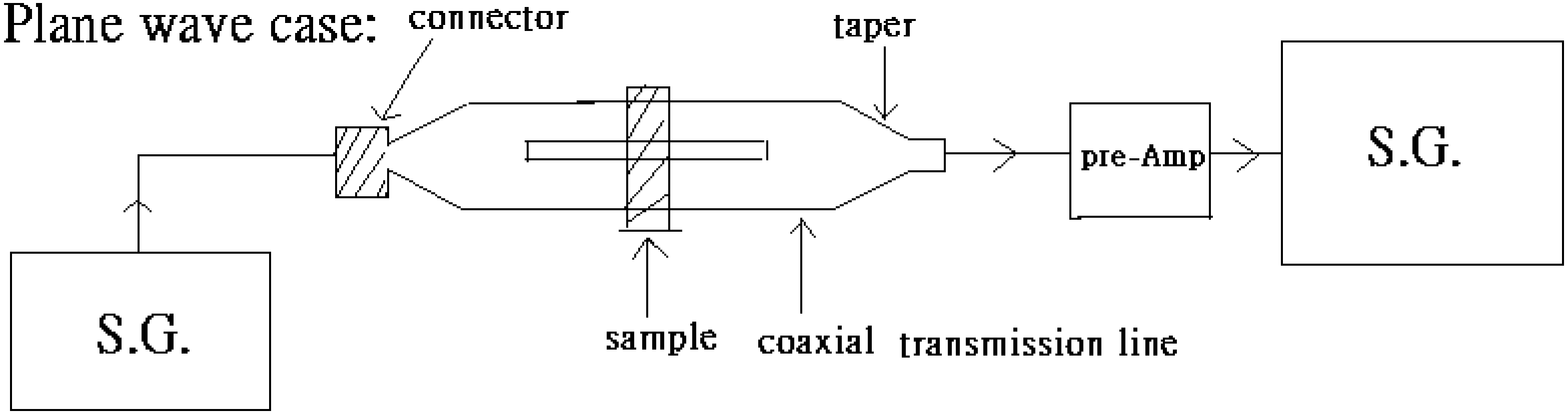
Measurement of SE

Method 1: EN50147-1



b. Measurement of S.E.

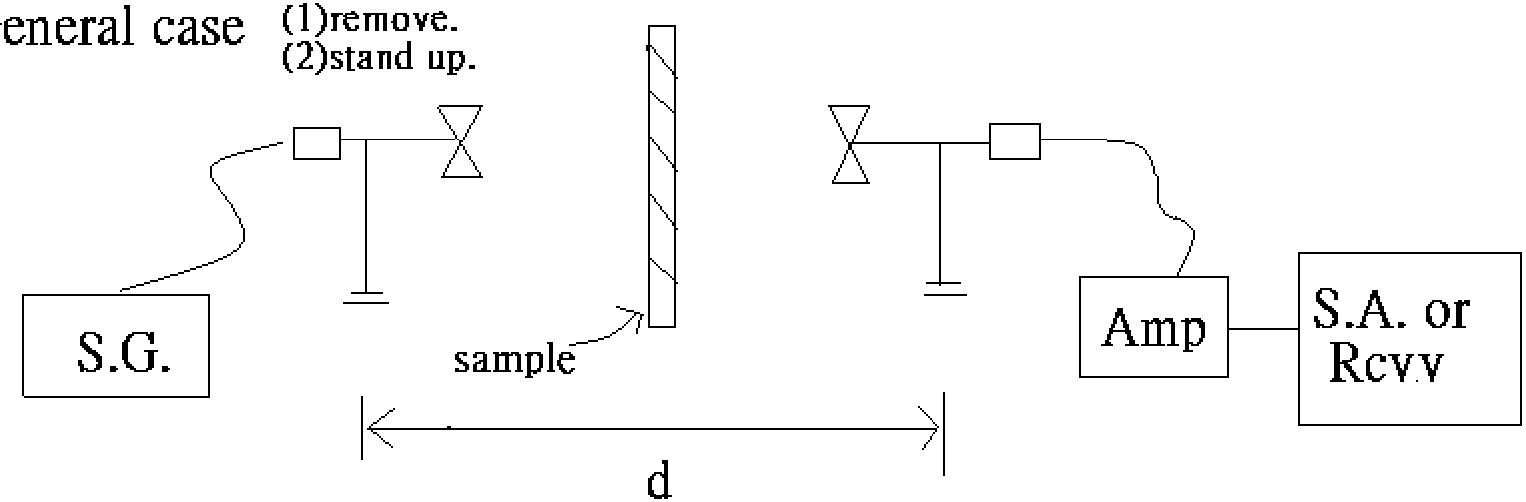
(1)Plane wave case:



$$S.E. = 20\log\left|\frac{V_{ref}}{V_{sample}}\right|$$

(2)General case

(1)remove.
(2)stand up.



Measurement of SE

Method two: Coaxial transmission line model

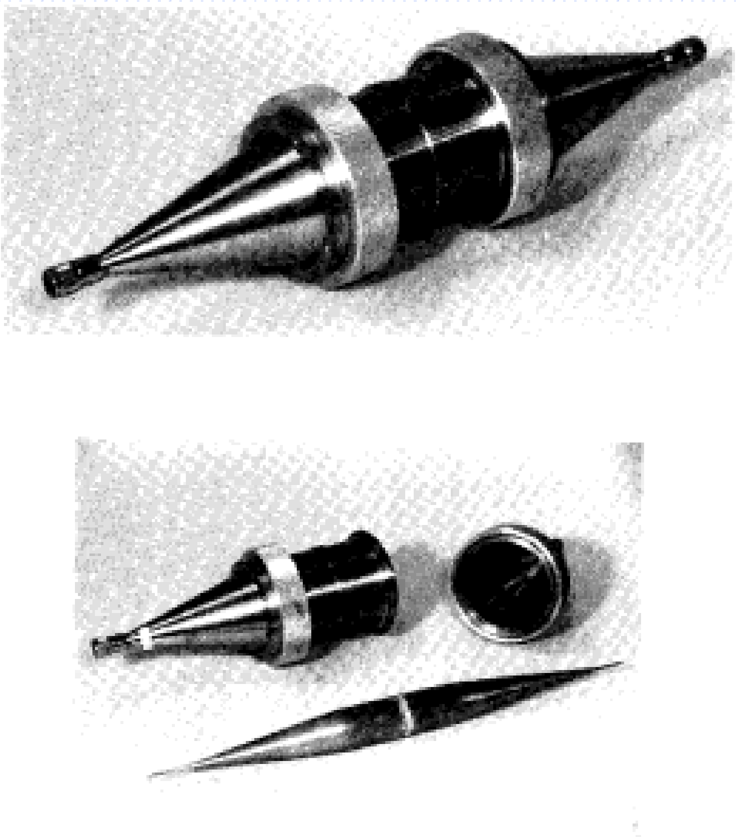


Fig. 2. Continuous-conductor coaxial transmission-line holder.