Nevertheless, the shielding effectiveness given in (10.2) can be broken into the product of three terms each representing one of the phenomena of *reflection loss, absorption loss, and multiple reflections.* In decibels these factors add to give

$$\mathrm{SE}_{\mathrm{dB}} = R_{\mathrm{dB}} + A_{\mathrm{dB}} + M_{\mathrm{dB}} \tag{10.4}$$

where R represents the reflection loss caused by reflection at the left and right interfaces, A represents the absorption loss of the wave as it proceeds through the barrier, and M represents the additional effects of multiple rereflections and transmissions. Observe that the rereflections will create fields that will add to the initial field transmitted across the right interface. Thus the multiple-reflection factor M will be a negative number and will, in general, reduce the shielding effectiveness (since R and A will be positive). We now embark on a quantitative determination of these factors that contribute to the shielding effectiveness of a barrier. In addition to the following derivations, the reader is referred to [3–5,10] for similar developments.

10.2 SHIELDING EFFECTIVENESS: FAR-FIELD SOURCES

In this section we will assume that the source for the field that is incident on the barrier is sufficiently distant from the barrier that the incident field resembles a uniform plane wave, whose properties are discussed in Appendix B. We first determine the exact solution for the shielding effectiveness, and will then determine this in an approximate fashion to show that the two methods yield the same results for shields that are constructed from "good conductors" whose thickness t is much greater than a skin depth at the frequency of the incident wave.

10.2.1 Exact Solution

In order to obtain the exact solution for the shielding effectiveness of a metallic barrier, we solve the problem illustrated in Fig. 10.4. A conducting shield of thickness t, conductivity σ, permittivity $\epsilon = \epsilon_0$, and permeability μ has an incident uniform plane wave incident on its leftmost surface. The medium on either side of the shield is assumed, for practical reasons, to be free space. A rectangular coordinate system is used to define the problem, with the left surface lying in the xy plane at $z = 0$ and the right surface located at $z = t$. Forward- and backward-traveling waves are present in the left medium and in the shield according to the general properties of the solution of Maxwell's equations. Only a forward-traveling wave is postulated in the medium to the right of the shield, since we reason that there is no additional barrier to create a reflected field. The general forms of these fields are (see Section B6.2 and [9,10]):

$$\vec{\hat{E}}_i = \hat{E}_i e^{-j\beta_0 z}\vec{a}_x \tag{10.5a}$$

$$\vec{\hat{H}}_i = \frac{\hat{E}_i}{\eta_0} e^{-j\beta_0 z}\vec{a}_y \tag{10.5b}$$

$$\vec{\hat{E}}_r = \hat{E}_r e^{j\beta_0 z}\vec{a}_x \tag{10.5c}$$

$$\vec{\hat{H}}_r = -\frac{\hat{E}_r}{\eta_0} e^{j\beta_0 z}\vec{a}_y \tag{10.5d}$$

$$\vec{\hat{E}}_1 = \hat{E}_1 e^{-\hat{\gamma} z}\vec{a}_x \tag{10.5e}$$

$$\vec{\hat{H}}_1 = \frac{\hat{E}_1}{\hat{\eta}} e^{-\hat{\gamma} z}\vec{a}_y \tag{10.5f}$$

$$\vec{\hat{E}}_2 = \hat{E}_2 e^{\hat{\gamma} z}\vec{a}_x \tag{10.5g}$$

$$\vec{\hat{H}}_2 = -\frac{\hat{E}_2}{\hat{\eta}} e^{\hat{\gamma} z}\vec{a}_y \tag{10.5h}$$

$$\vec{\hat{E}}_t = \hat{E}_t e^{-j\beta_0 z}\vec{a}_x \tag{10.5i}$$

$$\vec{\hat{H}}_t = \frac{\hat{E}_t}{\eta_0} e^{-j\beta_0 z}\vec{a}_y \tag{10.5j}$$

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

$$\beta_0 = \omega\sqrt{\mu_0 \epsilon_0} \tag{10.6a}$$

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \tag{10.6b}$$

and the propagation constant and intrinsic impedance of the shield are

$$\begin{aligned}\hat{\gamma} &= \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \\ &= \alpha + j\beta\end{aligned} \tag{10.7a}$$

$$\begin{aligned}\hat{\eta} &= \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \\ &= \eta\underline{/\theta_\eta}\end{aligned} \tag{10.7b}$$

The magnitude of the incident field $\hat{E}_i$ is assumed known. In order to determine the remaining amplitudes $\hat{E}_r$, $\hat{E}_1$, $\hat{E}_2$, and $\hat{E}_t$, we need four equations. These are generated by enforcing the boundary conditions on the field vectors at the two boundaries, $z = 0$ and $z = t$. Continuity of the tangential components of the electric field at the two interfaces gives

$$\vec{\hat{E}}_i|_{z=0} + \vec{\hat{E}}_r|_{z=0} = \vec{\hat{E}}_1|_{z=0} + \vec{\hat{E}}_2|_{z=0} \tag{10.8a}$$

$$\vec{\hat{E}}_1|_{z=t} + \vec{\hat{E}}_2|_{z=t} = \vec{\hat{E}}_t|_{z=t} \tag{10.8b}$$

Continuity of the tangential components of the magnetic field at the two interfaces gives

$$\vec{\hat{H}}_i|_{z=0} + \vec{\hat{H}}_r|_{z=0} = \vec{\hat{H}}_1|_{z=0} + \vec{\hat{H}}_2|_{z=0} \tag{10.9a}$$

$$\vec{\hat{H}}_1|_{z=t} + \vec{\hat{H}}_2|_{z=t} = \vec{\hat{H}}_t|_{z=t} \tag{10.9b}$$

Substituting the forms given in (10.5) gives the required four equations as

$$\hat{E}_i + \hat{E}_r = \hat{E}_1 + \hat{E}_2 \tag{10.10a}$$

$$\hat{E}_1 e^{-\hat{\gamma}t} + \hat{E}_2 e^{\hat{\gamma}t} = \hat{E}_t e^{-j\beta_0 t} \tag{10.10b}$$

$$\frac{\hat{E}_i}{\eta_0} - \frac{\hat{E}_r}{\eta_0} = \frac{\hat{E}_1}{\hat{\eta}} - \frac{\hat{E}_2}{\hat{\eta}} \tag{10.10c}$$

$$\frac{\hat{E}_1}{\hat{\eta}} e^{-\hat{\gamma}t} - \frac{\hat{E}_2}{\hat{\eta}} e^{\hat{\gamma}t} = \frac{\hat{E}_t}{\eta_0} e^{-j\beta_0 t} \tag{10.10d}$$

Solving these equations gives the ratio of the incident and transmitted waves as [10]

$$\frac{\hat{E}_i}{\hat{E}_t} = \frac{(\eta_0 + \hat{\eta})^2}{4\eta_0\hat{\eta}} \left[1 - \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 - \hat{\eta}} \right)^2 e^{-2t/\delta} e^{-j2\beta t} \right] e^{t/\delta} e^{j\beta t} e^{-j\beta_0 t} \tag{10.11}$$

Equation (10.11) is the *exact expression* for the ratio of the electric field that is incident on the boundary and the electric field that is transmitted through the boundary. We have substituted the relation $\hat{\gamma} = \alpha + j\beta$ from (10.7a) and also $\alpha = 1/\delta$ (assuming that the barrier material is a good conductor), where δ is the skin depth for the barrier material at the frequency of the incident wave:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{10.12}$$

We can, however, make some reasonable approximations to reduce this to a result derived by approximate means in the following sections. This will not only simplify the result but will also demonstrate that the same result can be derived by approximate methods without any significant loss in accuracy, as we will do in the next section.

In order to simplify (10.11), we will assume that the barrier is constructed from a "good conductor," so that the intrinsic impedance of the conductor is much less than that of free space: $\hat{\eta} \ll \eta_0$. Therefore we may approximate

$$\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}} \cong 1 \tag{10.13}$$

Also we assume that the skin depth δ is much less than the barrier thickness t. Thus

$$\begin{aligned} e^{-\hat{\gamma}t} &= e^{-\alpha t} e^{-j\beta t} \\ &= e^{-t/\delta} e^{-j\beta t} \\ &\ll 1 \quad \text{for } t \gg \delta \end{aligned} \tag{10.14}$$

Substituting these into the exact result given in (10.11) and taking the absolute value of the result gives

$$\begin{aligned} \left|\frac{\hat{E}_i}{\hat{E}_t}\right| &= \left|\frac{(\eta_0 + \hat{\eta})^2}{4\eta_0\hat{\eta}}\right| e^{t/\delta} \\ &\cong \left|\frac{\eta_0}{4\hat{\eta}}\right| e^{t/\delta} \end{aligned} \tag{10.15)}$$

Taking the logarithm of this result in order to express the shielding effectiveness in dB in accordance with (10.2) gives

$$\mathrm{SE_{dB}} \cong \underbrace{20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right|}_{R_{\mathrm{dB}}} + \underbrace{20\log_{10} e^{t/\delta}}_{A_{\mathrm{dB}}} + M_{\mathrm{dB}} \tag{10.16a}$$

The multiple-reflection loss in (10.4) is evidently the middle term of (10.11):

$$\begin{aligned} M_{\mathrm{dB}} &= 20\log_{10}\left|1 - \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)^2 e^{-2t/\delta} e^{-j2\beta t}\right| \\ &\cong 20\log_{10}|1 - e^{-2t/\delta} e^{-j2t/\delta}| \end{aligned} \tag{10.16b}$$

which can be neglected for shields that are constructed of good conductors, $\hat{\eta} \ll \eta_0$, and whose thicknesses are much greater than a skin depth, $t \gg \delta$. We have also substituted $\beta = \alpha = 1/\delta$, assuming the barrier is constructed from a good conductor. (See Appendix B, Section B.6.4.) Observe that this term is of the form $1 - \hat{\Gamma}_{\mathrm{in}}^2$, where $\hat{\Gamma}_{in} = [(\eta_0 - \hat{\eta})/(\eta_0 + \hat{\eta})]e^{-2\hat{\gamma}t}$ is the reflection coefficient at the right boundary referred to the left boundary. The multiple-reflection term is approximately unity ($M_{dB} \simeq 0$) for barrier thicknesses that are thick compared with a skin depth, $t \gg \delta$, and is of no consequence. However, for barrier thicknesses that are thin compared with a skin depth, $t \ll \delta$, the multiple-reflection factor is negative (in dB). In this case, multiple reflections reduce the shielding effectiveness of the barrier. For example, for $t/\delta = 0.1$, Eq. (10.16b) gives $M_{dB} = -11.8$ dB.

The separation of the exact result into a component due to reflection, a component due to absorption, and a component due to multiple reflections as in equation (10.4) is evident in (10.16a). This result will be derived by approximate methods in the following section.

10.2.2 Approximate Solution

We now consider deriving the previous result *under the assumption 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., $t \gg \delta$.* These assumptions are usually inherent in a well-designed shield and thus are not restrictive from a practical standpoint. The basic idea is illustrated in Fig. 10.6. First, it is worth noting that this approximate solution is analogous to the problem of analyzing the overall gain of cascaded amplifiers. In that problem we compute the input impedance of the first stage, using the input impedance of the second stage as the load for the first. Then we can compute the ratio of the output voltage of the first stage to its input voltage. Next we compute the ratio of the output voltage of the second stage to its input voltage, using the input impedance of the third stage as the load for the second stage. This process continues until we finally compute the gain of the last stage. The overall gain of the cascade is then the product of the gains of the individual stages. This technique takes into account the loading of each stage on the preceding stage, and this loading generally cannot be neglected. However, if the input impedances of the individual stages are quite large, as is generally the case for FET and vacuum-tube amplifiers, then this loading can be ignored and the overall gain of the cascade can be computed as the gains of the individual, *isolated* stages.

10.2.2.1 Reflection Loss The approximate analysis technique we will use is the direct analogy of the method for analyzing cascaded amplifiers described above. Assuming that the barrier thickness is much greater than a skin depth at the frequency of the incident wave, the portion of the incident wave that is transmitted across the left interface in Fig. 10.4, $\hat{E}_1$, is greatly attenuated by the time it reaches the right interface. Thus the reflected wave $\hat{E}_2$, when it arrives at the left interface, is not of much consequence and so contributes little to the total reflected wave $\hat{E}_r$. ($\hat{E}_2$ is also greatly attenuated as it travels from the second interface back to the left interface). Therefore we can approximately compute the portion of the incident wave that is transmitted across the left interface, $\hat{E}_1$, by assuming that the barrier is infinitely thick and therefore assuming that $\hat{E}_2 = 0$. This then becomes

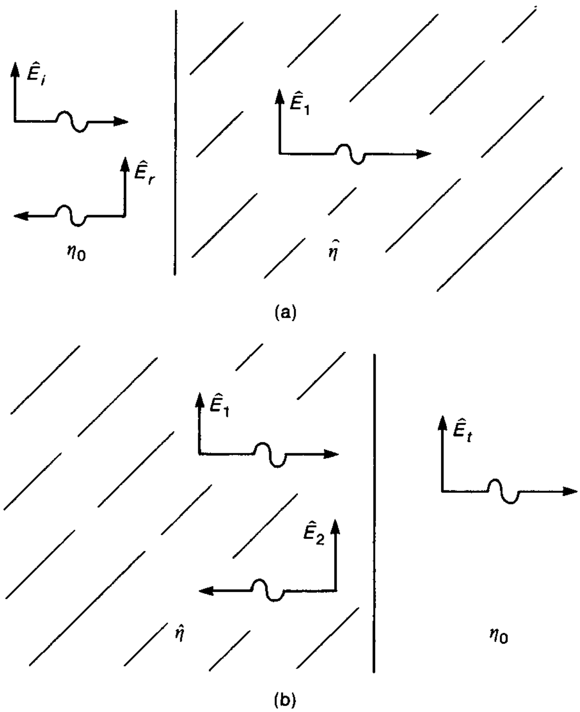

FIGURE 10.6 Approximate calculation of shielding effectiveness for uniform plane waves.

the basic problem considered in Section 7.6.2 of Chapter 7, and is illustrated in Fig. 10.6a. The transmission coefficient becomes

$$\frac{\hat{E}_1}{\hat{E}_i} \cong \frac{2\hat{\eta}}{\eta_0 + \hat{\eta}} \tag{10.17}$$

The next basic problem occurs at the right interface, as illustrated in Fig. 10.6b, and is again related to the basic problem considered in Section 7.6.2 of Chapter 7. The transmission coefficient for this case gives

$$\frac{\hat{E}_t}{\hat{E}_1} \cong \frac{2\eta_0}{\eta_0 + \hat{\eta}} \tag{10.18}$$

Note that for this case the intrinsic impedance of the medium for the transmitted wave is η_0 and the intrinsic impedance for the incident wave is $\hat{\eta}$. For the first half of this problem the intrinsic impedance of the medium for the transmitted wave is $\hat{\eta}$ and the intrinsic impedance for the incident wave is η_0. Taking the product of (10.17) and (10.18) gives the ratio of the transmitted field and the incident field *in the absence of attenuation* as

$$\begin{aligned}\frac{\hat{E}_t}{\hat{E}_i} &= \frac{\hat{E}_t}{\hat{E}_1}\frac{\hat{E}_1}{\hat{E}_i} \\ &= \frac{2\eta_0}{\eta_0 + \hat{\eta}}\frac{2\hat{\eta}}{\eta_0 + \hat{\eta}} \\ &= \frac{4\eta_0\hat{\eta}}{(\eta_0 + \hat{\eta})^2} \end{aligned} \tag{10.19}$$

Note that because $\hat{\eta} \ll \eta_0$, (10.17) is much smaller than (10.18). Thus *the transmission coefficient is very small at the first boundary, and is approximately two at the second boundary.* Thus *very little of the electric field is transmitted through the first* (*left*) *boundary.* The reflection coefficient at the first (left) interface is $\Gamma_1 = (\hat{\eta} - \eta_0)/(\hat{\eta} + \eta_0) \cong -1$, and the electric field is effectively "shorted out" by the good conductor. The reflection coefficient at the second (right) boundary is $\Gamma_2 = (\eta_0 - \hat{\eta})/(\eta_0 + \hat{\eta}) \cong +1$. These are analogous to the voltage reflections at the end of a short-circuited (left boundary) or open-circuited (right boundary) transmission line. Thus the majority of the electric field that is incident on each interface is reflected. However, because very little of the electric field is transmitted through the first boundary, it is of little consequence that the reflection coefficient at the second boundary is approximately unity! The reflection loss term in (10.4) is therefore

$$\begin{aligned} R_{\mathrm{dB}} &= 20\log_{10}\left|\frac{\hat{E}_i}{\hat{E}_t}\right| \\ &= 20\log_{10}\left|\frac{(\eta_0 + \hat{\eta})^2}{4\eta_0\hat{\eta}}\right| \\ &\cong 20\log_{10}\left|\frac{\eta_0}{4\hat{\eta}}\right| \end{aligned} \tag{10.20}$$

where we have substituted the approximation $\hat{\eta} \ll \eta_0$.

It is instructive to consider the magnetic field transmissions. Recall from Chapter 7 that the reflection and transmission coefficients were derived for the electric field only, and could not be used for the magnetic field. If we wish to determine the reflected and transmitted magnetic fields, we need to divide the electric fields by the appropriate intrinsic impedances to give

$$\begin{aligned} \frac{\hat{H}_1}{\hat{H}_i} &= \frac{\hat{E}_1/\hat{\eta}}{\hat{E}_i/\eta_0} \\ &= \frac{\hat{E}_1}{\hat{E}_i}\frac{\eta_0}{\hat{\eta}} \\ &= \frac{2\eta_0}{\eta_0 + \hat{\eta}} \end{aligned} \tag{10.21}$$

Similarly, we obtain

$$\begin{aligned}\frac{\hat{H}_t}{\hat{H}_1} &= \frac{\hat{E}_t/\eta_0}{\hat{E}_1/\hat{\eta}} \\ &= \frac{\hat{E}_t}{\hat{E}_1}\frac{\hat{\eta}}{\eta_0} \\ &= \frac{2\hat{\eta}}{\eta_0+\hat{\eta}}\end{aligned} \tag{10.22}$$

Taking the product of (10.21) and (10.22) gives the ratio of the transmitted and incident magnetic field intensities:

$$\begin{aligned}\frac{\hat{H}_t}{\hat{H}_i} &= \frac{\hat{H}_t}{\hat{H}_1}\frac{\hat{H}_1}{\hat{H}_i} \\ &= \frac{2\hat{\eta}}{\eta_0+\hat{\eta}}\frac{2\eta_0}{\eta_0+\hat{\eta}} \\ &= \frac{4\eta_0\hat{\eta}}{(\eta_0+\hat{\eta})^2}\end{aligned} \tag{10.23}$$

Comparing (10.23) and (10.19) shows that *the ratio of the transmitted and incident electric fields are identical to the ratio of the transmitted and incident magnetic fields*. However, there is one important difference: *the primary transmission of the magnetic field occurs at the left interface, whereas the primary transmission of the electric field occurs at the right interface*. [See (10.17), (10.18), (10.21), and (10.22).] Therefore the attenuation of the magnetic field as it passes through the boundary is more important than is the attenuation of the electric field. This points out that "thick" boundaries have more effect on shielding against magnetic fields than electric fields (because of this attenuation of the magnetic field as it travels through the boundary).

Since the primary transmission of the electric field occurs at the second boundary, shield thickness is not of as much importance as it is for magnetic field shielding, in which the primary transmission occurs at the first boundary. Attenuation of the barrier is of more consequence in magnetic field shielding, since there is considerable transmission of the magnetic field at the first boundary. Therefore effective shields for electric fields can be constructed from thin shields, which effectively "short out" the electric field at the first boundary.

10.2.2.2 Absorption Loss This previous result assumed that the barrier thickness was much greater than a skin depth, so that we could "uncouple" the calculation of the reflections and transmissions at the two interfaces. However, in taking the product of the two transmission coefficients as in (10.19), we are assuming that $\hat{E}_1$ is the same amplitude at the left and right interfaces. But the magnitude of $\hat{E}_1$ at the right interface will be reduced substantially from its value at the left interface by the factor $e^{-t/\delta}$. This attenuation can be easily accounted for—simply multiply (10.19) by $e^{-t/\delta}$. Thus the *absorption factor* accounting for attenuation becomes

$$A = e^{t/\delta} \tag{10.24}$$

In decibels this becomes

$$A_{\text{dB}} = 20 \log_{10} e^{t/\delta} \tag{10.25}$$

10.2.2.3 Multiple-Reflection Loss In the previous approximate calculations we have assumed that any "secondary reflections" are of no consequence, since they will have suffered substantial attenuation as they travel back and forth through the barrier. If the barrier thickness is not much greater than a skin depth, as was assumed, then the rereflections and transmissions may be important. This is particularly true for magnetic fields, since the primary transmission occurs at the first boundary, and thus these multiple reflections can be more significant for magnetic field shielding. In the case of multiple reflections that are significant they are accounted for with a *multiple-reflection factor* given in (10.16b) and illustrated in Fig. 10.7a. The total transmitted electric field is the sum of the primary and secondary transmitted waves at the right interface as

$$\begin{aligned} \hat{E}_t &= \hat{E}_{t1} + \hat{E}_{t2} + \hat{E}_{t3} + \cdots \\ &= \hat{E}_{t1}(1 + \Delta_2 + \Delta_3 + \cdots) \end{aligned} \tag{10.26}$$

where $\hat{E}_{t1}$ is the first electric field transmitted across the right interface which was considered to be the total transmitted field in the previous approximate solution that neglected these rereflections.

Consider the electric field transmitted across the left interface and incident on the right interface, $\hat{E}_{\text{in}}$, in Fig. 10.7. A portion of this is transmitted across the right interface,

$$\hat{E}_{t1} = \frac{2\eta_0}{\eta_0 + \hat{\eta}} \hat{E}_{\text{in}} \tag{10.27}$$

and a portion is reflected and sent back to the left interface,

$$\hat{E}_{r1} = \frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}} \hat{E}_{\text{in}} \tag{10.28}$$

These are obtained by multiplying by the transmission coefficient $\hat{T} = 2\eta_0/(\eta_0 + \hat{\eta})$ and the reflection coefficient $\hat{\Gamma} = (\eta_0 - \hat{\eta})/(\eta_0 + \hat{\eta})$ at the right interface. (See Section 7.6.2.) The reflected wave $\hat{E}_{r1}$ propagates back to the left interface and in so doing suffers attention and phase shift, $e^{-\hat{\gamma}t}$. At this left interface the incoming wave

$$\hat{E}_{r1} e^{-\hat{\gamma}t}$$

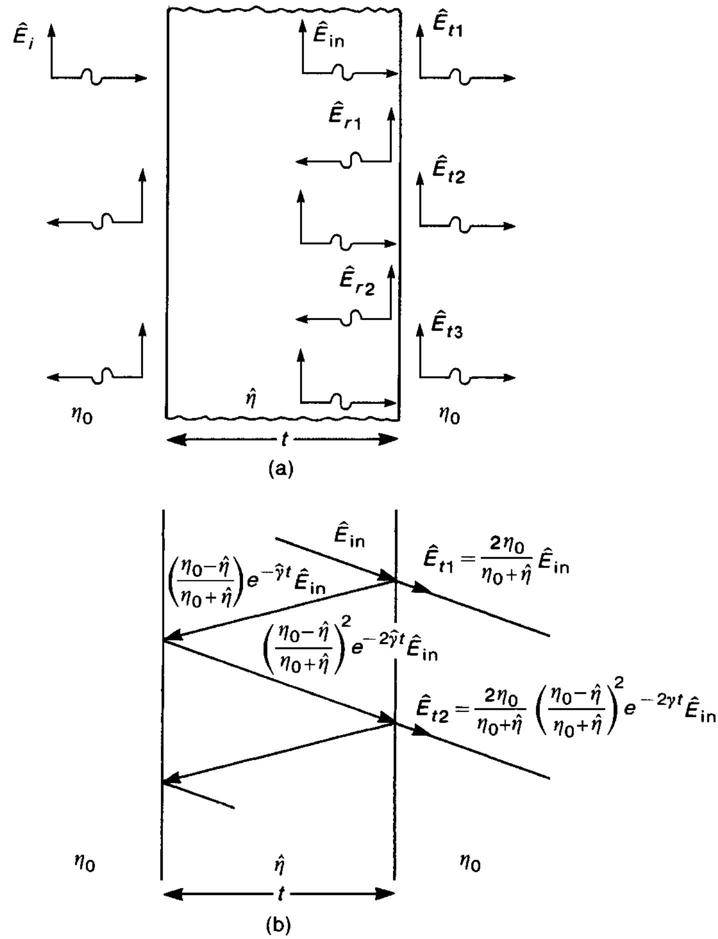

FIGURE 10.7 Illustration of the effect of multiple reflections within the barrier: (a) combining multiple transmissions; (b) calculation in terms of reflection and transmission coefficients.

is reflected as

$$\left(\frac{\eta_0 - \hat{\eta}}{\eta_0 - \hat{\eta}}\right)e^{-\hat{\gamma}t}E_{r1}$$

and propagated back to the second interface. When it arrives there it has been again multiplied by $e^{-\hat{\gamma}t}$ by virtue of propagating through the barrier again. Hence this second wave that is incident on the right interface is

$$\left(\frac{\eta_0 - \hat{\eta}}{\eta_0 - \hat{\eta}}\right)e^{-2\hat{\gamma}t}E_{r1}$$

A portion of this is transmitted across the right interface as

$$\hat{E}_{t2} = \frac{2\eta_0}{\eta_0 + \hat{\eta}}\left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)e^{-2\hat{\gamma}t}E_{r1}$$

Substituting (10.27) and (10.28) gives $\hat{E}_{t2}$ in terms of $\hat{E}_{t1}$ as

$$\begin{aligned}\hat{E}_{t2} &= \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)^2 e^{-2\hat{\gamma}t}\hat{E}_{t1}\\ &= \Delta^2\hat{E}_{t1}\end{aligned} \tag{10.29a}$$

where

$$\Delta = \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)e^{-\hat{\gamma}t} \tag{10.29b}$$

This continues giving the total transmitted electric field as

$$\begin{aligned}\hat{E}_t &= \hat{E}_{t1}(1 + \Delta^2 + \Delta^4 + \cdots)\\ &= \frac{\hat{E}_{t1}}{(1 - \Delta^2)}\end{aligned} \tag{10.30}$$

a summation that is valid for $|\Delta| < 1$ as is the case here.

The shielding effectiveness is

$$\begin{aligned}\mathrm{SE}_{\mathrm{dB}} &= 20\log_{10}\left|\frac{\hat{E}_i}{\hat{E}_t}\right|\\ &= 20\log_{10}\left|\frac{\hat{E}_i}{\hat{E}_{t1}}\right| + 20\log_{10}|1 - \Delta^2|\\ &= \underbrace{20\log_{10}\left|\frac{\hat{E}_i}{\hat{E}_{t1}}\right|}_{R_{\mathrm{dB}} + A_{\mathrm{dB}}}\\ &\quad \underbrace{+ 20\log_{10}\left|1 - \left(\frac{\eta_0 - \hat{\eta}}{\eta_0 + \hat{\eta}}\right)^2 e^{-2\hat{\gamma}t}\right|}_{M_{\mathrm{dB}}}\end{aligned} \tag{10.31}$$

10.2.2.4 Total Loss Combining the results given above gives the three components of the shielding effectiveness given in (10.4). The reflection loss is given in (10.20). Substituting the approximation for the intrinsic impedance of a good conductor as

$$\begin{aligned}\hat{\eta} &= \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \\ &= \sqrt{\frac{j\omega\mu}{\sigma}}\sqrt{\frac{1}{1+(j\omega\epsilon/\sigma)}} \quad \left(\begin{array}{c}\text{barrier is a}\\ \text{good conductor,}\\ \sigma/\omega\epsilon \gg 1\end{array}\right) \\ &\cong \sqrt{\frac{j\omega\mu}{\sigma}} \\ &= \sqrt{\frac{\omega\mu}{\sigma}}\underline{/45^\circ}\end{aligned} \tag{10.32}$$

and

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \tag{10.33}$$

into (10.20) gives

$$R_{\text{dB}} = 20\log_{10}\left(\frac{1}{4}\sqrt{\frac{\sigma}{\omega\mu_r\epsilon_0}}\right) \tag{10.34}$$

where we have assumed $\mu = \mu_0\mu_r$ and $\epsilon = \epsilon_0$. For the conductivity of metals, it is customary to refer to that of copper, which has a conductivity $\sigma_{\text{Cu}} = 5.8 \times 10^7$ S/m. Thus the conductivity of other metals is written as $\sigma = \sigma_{\text{Cu}}\sigma_r$, where σ_r is the *conductivity relative to copper.* Substituting this into (10.34) gives

$$R_{\text{dB}} = 168 + 10\log_{10}\left(\frac{\sigma_r}{\mu_r f}\right) \tag{10.35}$$

Observe that *the reflection loss is greatest at low frequencies and for high-conductivity metals.* Similarly, *magnetic materials*, $\mu_r > 1$, *degrade the reflection loss*. The reflection loss decreases at a rate of −10 dB/decade with frequency. As an example, consider a shield constructed of copper ($\mu_r = 1$). The reflection loss at 1 kHz is 138 dB. At 10 MHz the reflection loss is 98 dB. On the other hand, sheet steel has $\mu_r = 1000$ and $\sigma_r = 0.1$. At 1 kHz the reflection loss is 98 dB, and at 10 MHz it is reduced to 58 dB.

The absorption loss is given by (10.25). This can also be simplified. The skin depth is

$$\begin{aligned}\delta &= \frac{1}{\sqrt{\pi f \mu \sigma}} \\ &= \frac{0.06609}{\sqrt{f \mu_r \sigma_r}} \quad \text{m} \\ &= \frac{2.6}{\sqrt{f \mu_r \sigma_r}} \quad \text{in.} \\ &= \frac{2602}{\sqrt{f \mu_r \sigma_r}} \quad \text{mils}\end{aligned} \tag{10.36}$$

where we have written the result in various units. Substituting (10.36) into (10.25) gives

$$\begin{aligned}A_{\text{dB}} &= 20 \log_{10} e^{t/\delta} \\ &= \frac{20t}{\delta} \log_{10} e \\ &= \frac{8.686t}{\delta} \\ &= 131.4t\sqrt{f \mu_r \sigma_r} \quad (t \text{ in meters}) \\ &= 3.338t\sqrt{f \mu_r \sigma_r} \quad (t \text{ in inches})\end{aligned} \tag{10.37}$$

Equation (10.37) shows that the absorption loss increases with increasing frequency as $\sqrt{f}$ *on a decibel scale*. This is quite different from the absorption loss being proportional to the square root of frequency so that it increases at a rate of 10 dB/decade on a decibel scale. Therefore the absorption loss increases quite rapidly with increasing frequency. Ferromagnetic materials where $\mu_r \gg 1$ increase this loss over copper (assuming that $\mu_r \sigma_r \gg 1$). The absorption loss can also be understood in terms of the thickness of the shield relative to a skin depth, as is evident in (10.37):

$$\begin{aligned}A_{\text{dB}} &= \frac{8.686t}{\delta} \\ &= 8.7 \text{ dB} \qquad \text{for } \frac{t}{\delta} = 1 \\ &= 17.4 \text{ dB} \qquad \text{for } \frac{t}{\delta} = 2\end{aligned} \tag{10.38}$$

This illustrates the importance of skin depth in absorption loss.

Observe that the reflection loss is a function of the ratio σ_r/μ_r, whereas the absorption loss is a function of the product $\sigma_r \mu_r$. Table 10.1 shows these factors for various materials.

TABLE 10.1

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}

Figure 10.8 shows the components of the shielding effectiveness for a 20 mil thickness of copper as a function of frequency from 10 Hz to 10 MHz. Observe that the absorption loss is dominant above 2 MHz. Figure 10.9 shows the same data for steel (SAE 1045) for a 20 mil thickness. These data are plotted from 10 Hz to only 1 MHz. Note that for this material reflection loss dominates only below 20 kHz. These data indicate that reflection loss is the primary contributor to the shielding effectiveness at low frequencies for either ferrous or nonferrous shielding materials. At the higher frequencies ferrous materials increase the absorption loss and the total shielding effectiveness. It is worthwhile reiterating that for electric fields the primary transmission occurs at the second boundary, whereas for magnetic fields it occurs at the first boundary, so that absorption is more important for the reduction of magnetic fields.

Review Exercise 10.1 Determine the reflection loss for aluminum, brass, and stainless steel at 1 MHz.

***Answers*:** 106 dB, 102 dB, and 64 dB.

Review Exercise 10.2 Determine the skin depth in mils for aluminum, brass, and stainless steel at 1 MHz.

***Answer*:** 3.33 mils, 5.1 mils, and 0.82 mils.

Review Exercise 10.3 Determine the absorption loss for $\frac{1}{8}$-in. (125-mils)-thick aluminum, brass, and stainless-steel shields at 1 MHz.

***Answer*:** 326 dB, 213 dB, and 1320 dB.

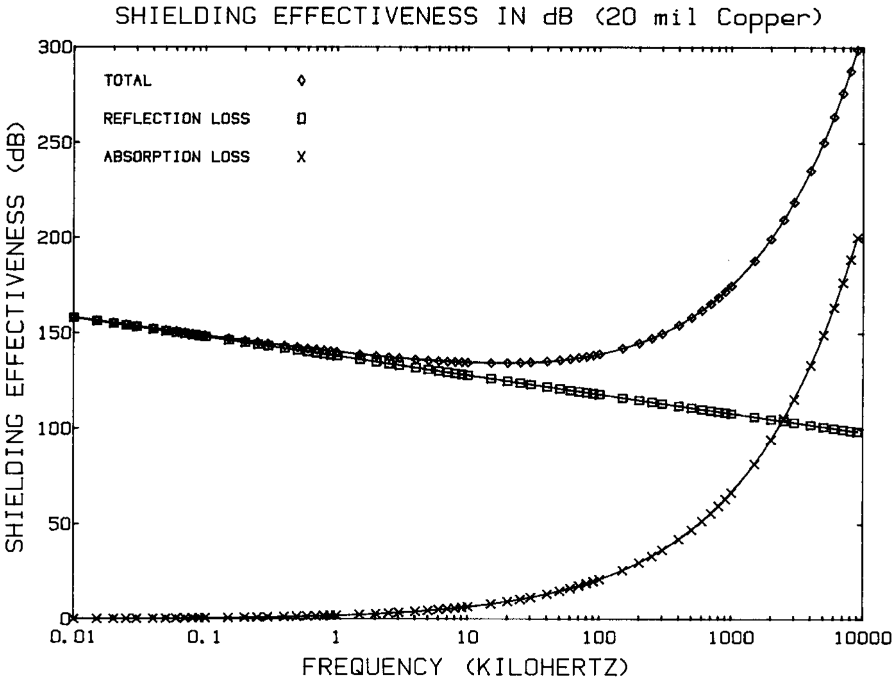

FIGURE 10.8 Shielding effectiveness of a 20 mil thickness of copper.

10.3 SHIELDING EFFECTIVENESS: NEAR-FIELD SOURCES

The previous analysis of shielding effectiveness assumed a uniform plane wave incident normal to the surface of the shield. This therefore assumes that the shield is in the far field of the source of the incident field. In this section we will consider *near-field sources.* We will find that the techniques for shielding depend on the *type of source*; whether the source is a *magnetic field source* or an *electric field source.* It must be pointed out that near fields are much more complicated in structure than are far fields (which are simple and resemble uniform plane waves). Hence, analysis of the effects of plane, conducting barriers on near fields is a very complicated process. The reader is referred to the ongoing analysis published in the literature. The near-field shielding for current loops is analyzed in [6,7], whereas the near-field shielding for line current sources is analyzed in [8].

It is unreasonable to expect that simple and highly accurate formulas can be obtained for near-field shielding as were obtained (exactly) for far-field shielding in the preceding sections. The following results are approximations to the exact results (which are very complicated). The heart of this approximate method is to replace the intrinsic impedance of free space, $\eta_0 = \sqrt{\mu_0/\epsilon_0}$, with the *wave impedance*, $\hat{Z}_w$, for the Hertzian (electric) dipole and the small magnetic loop (dipole) considered in Chapter 7. Although this is a somewhat crude approximation, it has