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A Study of the Electromagnetic Properties of Concrete Block Walls for Short Path Propagation Modeling

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For short propagation paths, correctly representing reflections of electromagnetic energy from surfaces is critical for accurate signal level predictions. In this paper, the method of homogenization is used to determine the effective material properties of composite material commonly used in construction. The reflection and transmission coefficients for block walls and other types of materials calculated with these homogenized effective material properties are presented. The importance of accurately representing the reflections for signal level prediction models is also investigated. It is shown that a 5- to 10-dB error in received signal strength can occur if the composite walls are not handled appropriately. Such accurate predictions of signal propagation over short distance is applicable to microcellular personal communications services deployments in urban canyons as well as indoor wireless private branch exchanges and local area networks.

Key words: composite walls; concrete walls; propagation modeling; reflection coefficient; homogenization; effective material properties

1. INTRODUCTION

Much work on long path propagation through urban settings has been done in the past [1]-[10]. In most of this work, little attention is given to accurate representation of the reflection coefficient (Γ) of a wave striking building surfaces. In this paper the problem of electromagnetic wave interaction with composite walls is addressed. Some examples used here are concrete block walls and other composite structures depicted in Figures 1 and 2.

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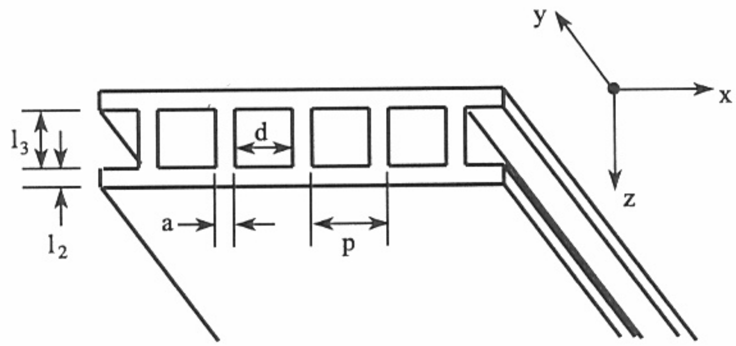
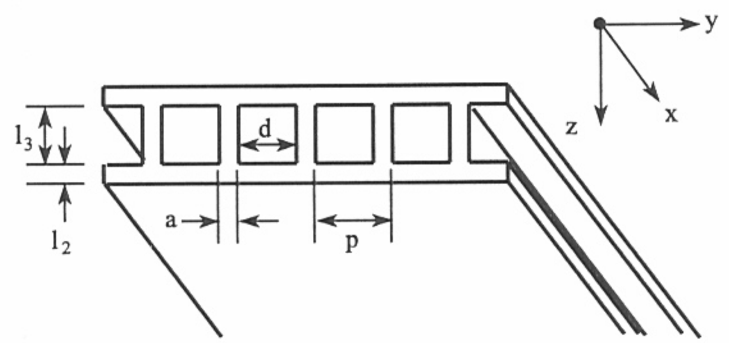


a)



b)

Figure 1. a) Illustration of a concrete block wall with its slabs oriented along the $y - axis$, b) Illustration of a concrete wall with it slabs oriented along the $x - axis$.

In the majority of the published work the reflection coefficients of the buildings are obtained by assuming that either the building materials are perfect conductors or that the building walls are single solid slabs of material with some assumed properties. For the most part this may very well be justified for long path propagation in urban canyons.

In long path propagation, the transmitting and receiving antennas are set a relatively large distance apart. The dominant contribution to the total signal for an urban canyon setting is waves that make one to two bounces off the building, take a direct path, and make one bounce off the ground (see Figure 3). In this case the waves that bounce off of buildings are incident at an angle close to grazing, or 90^o. Even though the angular dependence of

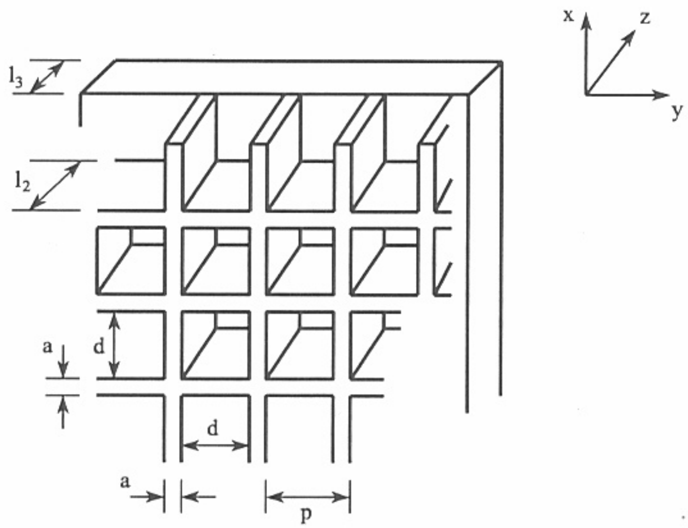


Figure 2. Illustration of a two-dimensional periodic block wall.

the reflection coefficient of a composite material can behave much differently than that of a perfect conductor or a single solid slab, this is not an important issue for long propagation paths. Therefore, regardless of the building's material, the actual reflection coefficient for large incident angles will approach that of a perfect conductor.

There is a growing need to predict signal levels for short propagation paths, in the range of 2-100 meters. Business campuses utilizing wireless private branch exchanges (PBXs) and wireless local area networks (LANs) to provide mobile voice and data communications, vehicular communications through urban canyons to nearby relays, and microcellular personal communications services (PCS) deployment in malls and airport are just a few examples. For short propagation paths like these, the accurate behavior of waves reflecting off walls can be very important.

Calculating the fields interaction (i.e. the reflection and transmission coefficient) of the composite structures similar to those shown in Figures 1 and 2 is a classic problem (see [11]-[27]). These techniques range from analytical techniques like Floquet analysis and mode matching to full numerical approaches like method of moments (MOM), finite element, and finite

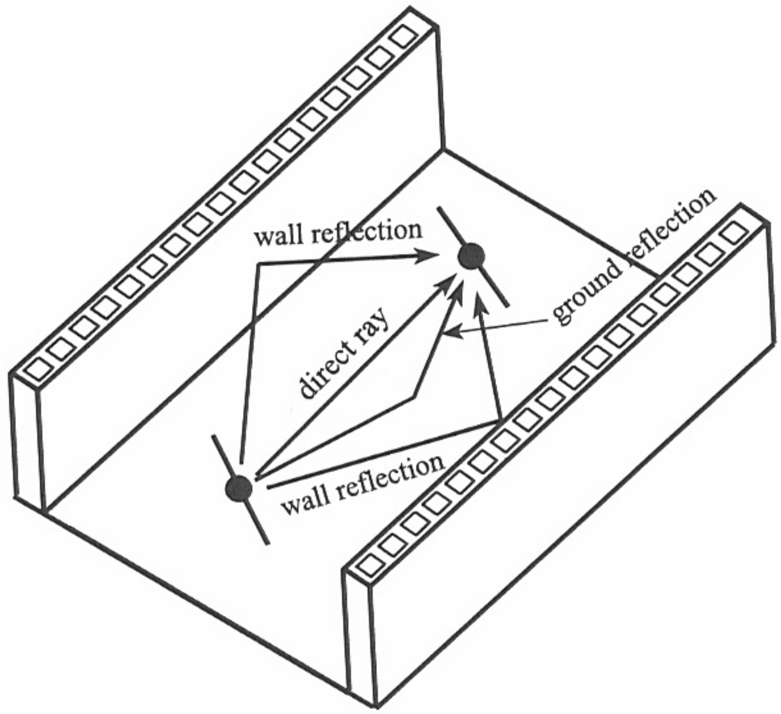


Figure 3. Illustration of the rays in the four-ray model.

difference methods. These techniques are capable of high accuracy, but are computationally intensive and hence do not lend themselves to ready use in signal prediction models. For short path signal prediction models (like ray tracing and other geometric optic models), efficient closed form expressions for calculating both the the reflection and transmission coefficients for composite structures are desired.

In this paper, we introduce expressions for the effective material properties for some commonly used composite building materials. These expressions for the effective material properties can be used to efficiently obtain the reflection and transmission coefficients for walls composed of composite materials. With these reflection and transmission properties we investigate the importance of accurately representing the interaction of the composite walls for the prediction of received signal strength (RSS) over short distances. The paper is organized as follows: following the introduction, Section 2 discusses the technique of homogenization, showing how the equivalent material properties for composite walls can be obtained. Expressions are then given for the effective material properties for both singly and doubly periodic structures. In Section 3 the equations needed for calculating the reflection and transmission coefficient for an obliquely incident plane wave (either perpendicular or parallel polarizations) are introduced. In Section 4 results from a singly periodic structure for different orientations and polarizations are presented. In Section 5 results for doubly periodic structures are presented. Also in Section 4 and 5, the importance of accurately representing the reflection properties of walls for signal level prediction models is investigated. Finally, in Section 6 a discussion on the validity of the expressions presented here is given.

2. EFFECTIVE MATERIAL PROPERTIES OBTAINED FROM HOMOGENIZATION

The problem at hand is to determine the reflection and/or transmission coefficient for a field incident onto the composite periodic structures illustrated in Figures 1 and 2. The concrete block wall in Figure 1 is equivalent to a five layer medium depicted in Figure 4. Layers 1 and 5 are free space, layers 2 and 4 have the material properties of the concrete, and layer 3 represents a one-dimensional periodic structure. The two-dimensional composite wall in Figure 2 is equivalent to a four-layer medium depicted in Figure 5. Layers 1 and 4 are free space, layer 3 has the material properties of the concrete, and layer 2 represents a two-dimensional periodic structure. In order to calculate the reflection and/or transmission coefficient for these composite structures the field's interaction with the periodic sections labeled as layer 3 (for the one-dimensional structure of Figure 4) and layer 2 (for the two-dimensional structure of Figure 5) must be determined.

Recently, a method for analyzing periodic structures known as homogenization has been used to solve problems of this type when the period of the structure is small compared to the wavelength. Only a few of these published results are applicable to electromagnetic problems: [28] and [29] for a corrugated impedance surface, [30] and [31] for a wire grid and conducting strips, [32] for a rough perfectly and non-perfectly conducting rough surfaces, and [33]-[35] for analyzing pyramidal electromagnetic absorbers.

Even though the homogenization technique is based on the period of the structure being small compared to a wavelength, results given in [34] and [36]-[38] indicate that the homogenization models are accurate for periods at least as large as 1/2-1 free space wavelength and possibly even higher for lossy periodic structures. This is discussed in more detail in Section 6.

Homogenization is a technique utilized in the early 1970's, primarily by a group of French mathematicians (see [28] and [39]-[45]). This asymptotic technique is based on the method of multiple-scales associated with the microscopic and macroscopic field variations due to the periodic structure. In most situations, only the averaged (slowly varying) fields are of interest, and not the microstructure of the fields. Homogenization allows the separation of the average field from the microstructure. It is then possible to show that the averaged fields satisfy Maxwell's equations for some homogeneous media. The equivalent material properties of these homogeneous media are related to the properties of the composite structure.

With homogenization, the periodic layers of the composite structures (layer 3 in Figure 4 and layer 2 in Figure 5) can be replaced with a medium with an equivalent material property. Once the equivalent material property of the medium is determined, then the reflection and transmission coefficients of the composite structures can be efficiently obtained with either classical layered media approaches or by classical transmission line methods.

Homogenization uses asymptotic expansions and the concept of multiple-scales to expand the E and H fields in an asymptotic power series with both *slow* and *fast* variations. These slow and fast variations are associated with the microscopic and macroscopic field variations. With asymptotic power series of both the E and H fields, Maxwell's equations can be grouped

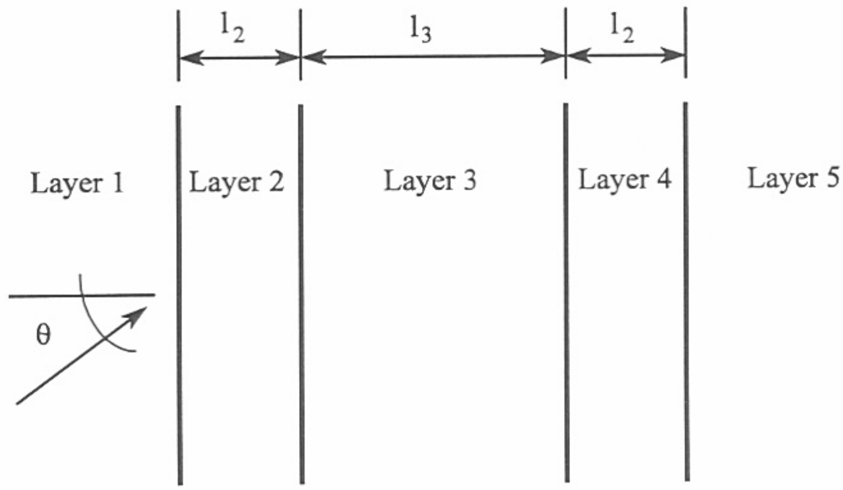


Figure 4. Equivalent layered media of a concrete block wall.

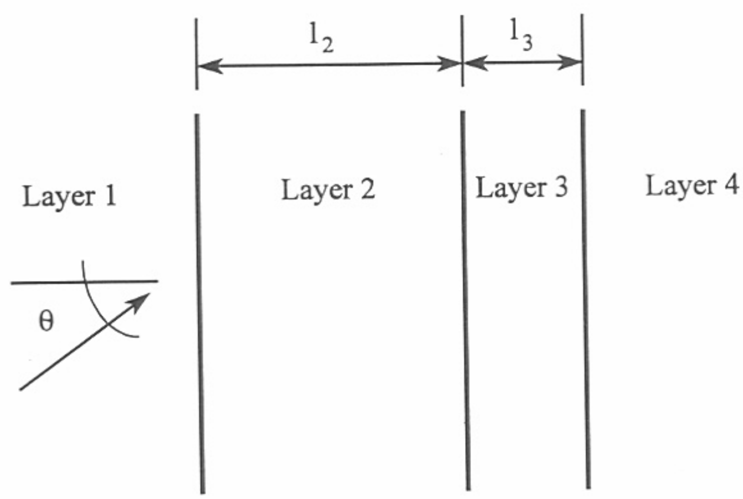


Figure 5. Equivalent layered media of a two-dimensional block wall.

in terms of different powers of the period (p) of the structure. The details of this procedure are found in [33].

Following this type of analysis, the zeroth order averaged fields $[(\bar{E}^o)_{\text{avg}}$ and $(\bar{H}^o)_{\text{avg}}]$ are related by the following:

$$\begin{aligned} \nabla \times (\bar{E}^o)_{\text{avg}} &= -j\omega \left[\mu^h\right] \cdot (\bar{H}^o)_{\text{avg}} \\ \nabla \times (\bar{H}^o)_{\text{avg}} &= -j\omega \left[\epsilon^h\right] \cdot (\bar{E}^o)_{\text{avg}} \ . \end{aligned} \tag{1}$$

This equation states that the average fields satisfy Maxwell's equations in an anisotropic homogeneous medium characterized by the tensors $\left[\epsilon^h\right]$ and $\left[\mu^h\right]$. These effective material properties are referred to as the homogenized permittivity $[\epsilon^h]$ and permeability $[\mu^h]$, and are defined by the following:

$$\begin{aligned} \left(\epsilon\bar{E}^o\right)_{\text{avg}} &\equiv \left[\epsilon^h\right] \cdot \left(\bar{E}^o\right)_{\text{avg}} \\ \left(\mu\bar{H}^o\right)_{\text{avg}} &\equiv \left[\mu^h\right] \cdot \left(\bar{H}^o\right)_{\text{avg}} \ . \end{aligned} \tag{2}$$

The average zero order fields $[(\bar{E}^o)_{\text{avg}}$ and $(\bar{H}^o)_{\text{avg}}]$ see the properties of the medium in terms of a single tensor quantity. The values of these tensors can be obtained from the solutions of the two-dimensional static source-free field problems that govern $\bar{E}^o$ and $\bar{H}^o$ (see [33]):

$$\begin{aligned} \nabla_\xi \times \bar{E}^o &= 0 \\ \nabla_\xi \times \bar{H}^o &= 0 \end{aligned} \tag{3}$$

and

$$\begin{aligned} \nabla_\xi \cdot (\epsilon\bar{E}^o) &= 0 \\ \nabla_\xi \cdot (\mu\bar{H}^o) &= 0 \end{aligned} \tag{4}$$

where ξ is the so-called $fast$ variable and is defined as the following:

$$\xi = \frac{1}{p}(x\bar{a}_x + y\bar{a}_y) \tag{5}$$

where p is the period of the structure.

Now that it has been shown that the averaged field sees the periodic medium as an effective anisotropic homogeneous region with tensor permittivity $[\epsilon^h]$ and $[\mu^h]$:

$$
\begin{aligned}
\left[\epsilon^h\right] &= \begin{bmatrix} \epsilon_x & 0 & 0 \\ 0 & \epsilon_y & 0 \\ 0 & 0 & \epsilon_x \end{bmatrix} \\
\left[\mu^h\right] &= \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_x \end{bmatrix} ,
\end{aligned}
\tag{6}
$$

we now need to determine the effective material properties of this region. There has been a great deal of attention in the past towards determining the effective properties of composite regions. For a survey of this work see [46].

For the one-dimensional periodic structure, the effective properties of layer 3 (see Figure 4) is needed. If the period (p) of the slab structure shown in Figure 6 is small compared to a wavelength in either medium, and also small compared to the skin depth, then the effective properties are given by [33], [17] and [47]-[50] as:

$$
\begin{aligned}
\epsilon_x^{-1} &= (1-g)\epsilon_o^{-1} + g\epsilon_a^{-1} \\
\mu_x^{-1} &= (1-g)\mu_o^{-1} + g\mu_a^{-1} \\
\epsilon_y = \epsilon_z &= (1-g)\epsilon_o + g\epsilon_a \\
\mu_y = \mu_z &= (1-g)\mu_o + g\mu_a
\end{aligned}
\tag{7}
$$

where $g = a/p$ (p and a are defined in Figure 1) is the relative volume of space occupied by the material, ϵ_a and μ_a are the complex parameters of the bulk material, and ϵ_o and μ_o are the free space values.

For the two-dimensional block wall shown Figure 7 (where $\epsilon_2 = \epsilon_o$ and $\epsilon_1 = \epsilon_a$), the longitudinal permittivity and permeability are known exactly ([46], [28] and [39]) as:

$$
\begin{aligned}
\epsilon_z &= (1-g)\epsilon_o + g\epsilon_a \\
\mu_z &= (1-g)\mu_o + g\mu_a
\end{aligned}
\tag{8}
$$

where $g = a^2/p^2$ (a and p are defined in Figure 2) is the volume fraction of space occupied by the material, and ϵ_a and μ_a are the complex parameters of the bulk material.

For this type of symmetric two-dimensional periodic structure, $\epsilon_t = \epsilon_x = \epsilon_y$, and $\mu_t = \mu_x = \mu_y$. Reference [33] indicates that the transverse permittivity (ϵ_t) and permeability

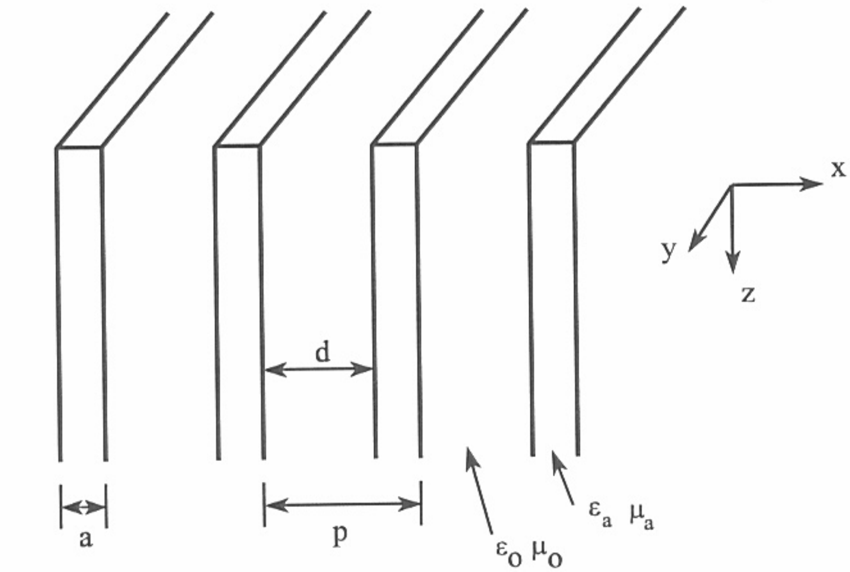


Figure 6. One-dimensional periodic structure.

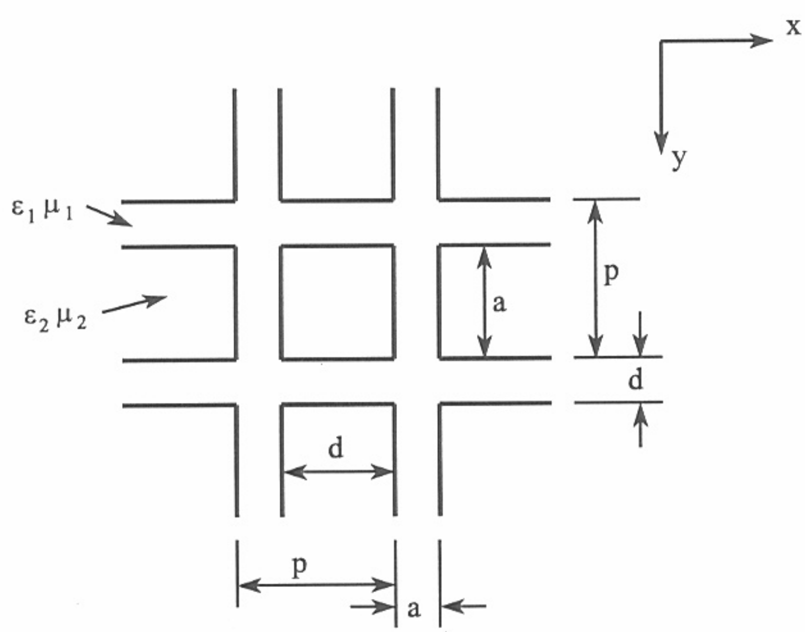


Figure 7. Two-dimensional periodic structure.

(μ_t) are not simple spatial averages as had often been assumed. There are no exact closed form expressions for the transverse material properties; however, upper and lower bounds for these properties can be found in [46].

Nakamura and Hirasawa [51] have done a numerical study of a similar periodic structure and they showed that the Hashin-Shtrikman upper bound given in [46] and [52] correlates very well to the effective material properties of this type of periodic structure. Thus, the transverse material properties can be approximated by the following:

$$\left.\begin{aligned} \epsilon_t &= \epsilon_a + \frac{1-g}{\frac{1}{\epsilon_a - \epsilon_o} + \frac{g}{2\epsilon_a}} \\ \mu_t &= \mu_a + \frac{1-g}{\frac{1}{\mu_a - \mu_o} + \frac{g}{2\mu_a}} \end{aligned}\right\} \tag{9}$$

where once again $g = a^2/p^2$ is the volume fraction of space occupied by the material.

In [33], a structure converse to the one shown in Figure 7, i.e., a dielectric surrounded by air (where $\epsilon_2 > \epsilon_1$), was analyzed. If the roles of the material properties in equation (9) are interchanged with Keller's scaling theorem [53] (such that $\epsilon_1 < \epsilon_2$), then the results given in equation (25) of [33] are obtained.

In general, the permittivity given in equations (7)-(9) is complex, resulting from the possibility that the material has a conductivity σ. For this scenario, the complex permittivity in these equations is expressed as:

$$\epsilon = \epsilon_r - j\frac{\sigma}{\epsilon_o \omega} \quad . \tag{10}$$

3. OBLIQUELY INCIDENT PLANE WAVE

We want to investigate the problem of a plane wave incident onto the medium that behaves like a uniaxially anisotropic, but homogeneous, material. The periodic structures shown in

Figures 6 and 7 can be replaced with an equivalent layer (Figure 8). The material properties of this effective layer can be given by either equation (7) (for the one-dimensional periodic structure) or by equations (8) and (9) (for the two-dimensional periodic structure). If the plane of incidence is the xz-plane (Figure 8), then we can assume $\partial/\partial y \equiv 0$. Maxwell's equations can now be decoupled into two independent sets of equations; one set for the perpendicular polarization (referred to as E-polarization):

$$\begin{aligned} \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= j\omega\epsilon_y E_y \\ \frac{\partial E_y}{\partial x} &= -j\omega\mu_z H_z \\ \frac{\partial E_y}{\partial z} &= -j\omega\mu_x H_x \end{aligned} \tag{11}$$

and one set for the parallel polarization (referred to as H-polarization):

$$\begin{aligned} \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= j\omega\mu_y H_y \\ \frac{\partial H_y}{\partial x} &= -j\omega\epsilon_z E_z \\ \frac{\partial H_y}{\partial z} &= -j\omega\epsilon_x E_x \end{aligned} \tag{12}$$

with an assumed time factor of $e^{j\omega t}$.

The x-dependent factor of the fields is given by: $e^{-jk_o x \sin\theta}$, which means that the derivatives with respect to x can be replaced by:

$$\frac{\partial}{\partial x} \rightarrow -jk_o \sin\theta \ . \tag{13}$$

With this, the following general set of equations for the electromagnetic fields is obtained in which the z component is eliminated:

$$\begin{aligned} \frac{dE(z)}{dz} &= -j\omega\mu_{eff} H(z) \\ \frac{dH(z)}{dz} &= -j\omega\epsilon_{eff} E(z) \end{aligned} \tag{14}$$

where for the perpendicular polarization:

$$E(x) = E_y(z) \qquad H(z) = -H_x(z) \tag{15}$$

$$\begin{aligned} \epsilon_{eff} &= \epsilon_y - \frac{\mu_o \epsilon_o \sin^2\theta}{\mu_z} \\ \mu_{eff} &= \mu_x \end{aligned} \tag{16}$$

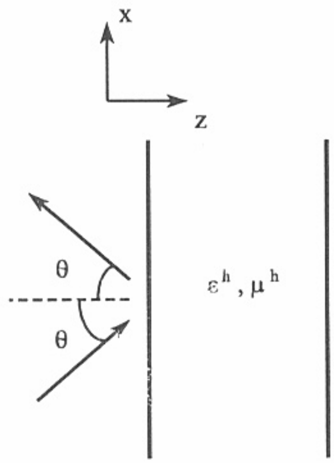


Figure 8. Equivalent anisotropic layer.

and for the parallel polarization:

$$E(x) = E_x(z) \qquad H(z) = H_y(z) \tag{17}$$

$$\begin{aligned} \epsilon_{eff} &= \epsilon_x \\ \mu_{eff} &= \mu_y - \tfrac{\mu_o \epsilon_o \sin^2\theta}{\epsilon_z} \ . \end{aligned} \tag{18}$$

With these expressions for the angular dependence on the effective material properties, we can now calculate reflection and transmission coefficients for composite structures.

4. REFLECTION FROM A CINDER BLOCK WALL

In this section, results for a one-dimensional periodic structure resembling a cinder block wall will be given (see Figures 1 and 4). Four block walls are analyzed: two different 14.5-cm (5.71-in) walls, one 7.2-cm (2.83-in) wall, and one 19.6-cm (7.72-in) wall. The dimensions of these different walls are shown in Table 1.

The 14.5-cm (5.71-in) block wall labelled block # 1 in Table 1 is represented as the layered structure shown in Figure 4, and has the following geometry: layers 1 and 5 are free space;