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ELECTROMAGNETIC ABSORPTION IN A MULTILAYERED MODEL OF MAN

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Abstract

A multilayered planar model is used to examine the dependence of whole body power absorption on the configuration of surface layers, e.g., skin, fat, muscle, which normally occur in biological bodies. It is found that the layering resonance for three-dimensional bodies (as opposed to the geometrical resonance) can be predicted quite accurately by a planar model. Calculations for a multilayered prolate spheroidal model of man predict a whole-body layering resonance at 1.8 GHz with a power absorption 34 percent greater than that predicted by a homogeneous model.

Introduction

Recent interest in quantifying both the hazardous and potentially beneficial effects of nonionizing electromagnetic radiation on man has been the impetus for a great deal of experimental and theoretical research. Of particular interest are calculations to determine the relationship between incident power density and the resulting absorbed power due to whole-body irradiation of man. Recent theoretical methods that have been used include a perturbation approach [1] useful for analyzing

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homogeneous ellipsoidal models and an integral equation method [2] for analyzing homogeneous prolate spheroidal models. The absorption characteristics of inhomogeneous irregular shaped models constructed of cubical subvolumes have been studied by volume integral moment method techniques [3, 4]. In these whole-body irradiation studies, the power absorption is determined as a function of the angle of incidence, polarization, and frequency of the incident electromagnetic wave. Usually the results are shown as a plot of specific absorption rate in W/kg versus frequency, where an incident power density of 1 mW/cm^2 is assumed. Typically, for a given angle of incidence and polarization, the power absorption increases relatively rapidly with frequency to a resonant peak and then slowly decreases to an asymptotic high frequency limit.

There is another interaction which takes place which has not been considered in recent whole-body calculations. Both homogeneous and inhomogeneous models have not accounted for the electromagnetic interaction due to the surface layering of biological bodies, e.g., the layers of skin, fat, and muscle. An investigation of these effects is the subject of this paper.

Absorption Effects Due to Layering

Early calculations to assess the biological significance of electromagnetic radiation used planar models consisting of skin, fat, and semi-infinite muscle layers [5]. Later a two-layered (fat and muscle) spherical model was used [6]. These earlier investigations are summarized in [7]. Both studies showed that the absorption characteristics are critically dependent on the number and thickness of the surface layers. More recent whole-body calculations have not considered the effect of surface layers. One reason for this is due to the unavailability of multilayered analytical solutions for any geometry other than the plane, infinite circular or elliptical cylinder, and sphere. In the case of numerical approaches, such as the volume moment method technique, practical limitations on the number of cells which may be used prohibit consideration of layering effects.

A six-layered sphere has recently been used to model the isolated head [8-10]. Of particular interest are results in [9] and [10] which compare the frequency dependent absorption in six-layered spheres with that in corresponding homogeneous spheres. One of the power absorption results in [9] has been recalculated and is shown in Fig. 1 as a plot of absorption efficiency versus frequency. This and subsequent multilayered sphere calculations were made using a Mie theory computer program based on the mathematical development in [8]. The absorption efficiency is the total power absorbed divided by the power incident on the geometrical cross section. An absorption efficiency greater than unity indicates that the influence of the body on the incident wave extends beyond the geometrical boundary. The absorption efficiency for the homogeneous brain tissue sphere increases with frequency until the maximum is reached and then slowly decreases. The amplitude and frequency of the resonance are dependent upon the size, shape, and dielectric characteristics of the model. This maximum absorption condition can be called the <u>geometrical</u> resonance. The absorption efficiency for the six-layered model has an additional resonance which is due to the impedance matching effects of the surface layers and at this resonance the absorption efficiency is almost 30 percent greater than that at the geometrical resonance. This second maximum absorption condition can be called the layering resonance.

The most interesting feature shown in Fig. 1 is that the presence of layering enhances the absorption of the spherical model. Another feature is that the geometrical and layering resonances appear to be independent of one another, i.e., the geometrical resonances of the homogeneous and layered spheres are almost identical, while the layering resonance of the six-layered sphere appears merely as an enhancement of the absorption over that of the homogeneous sphere.

Calculations for a homogeneous and six-layered planar model have been made for the same tissue thicknesses and dielectric characteristics as were used to obtain the results in Fig. 1. The calculations were made using conventional planar techniques [11]. The brain tissue core in the spherical model was assumed to extend to infinity in the planar model. These results are shown in Fig. 2. The planar model, which does not exhibit a geometrical resonance, does however show the same layering resonance as is observed in Fig. 1 for the layered spherical model. The location of the layering resonance and the enhancement of the absorption efficiency due to the layering are almost identical for the planar and spherical models. Taking the ratio of the layered to homogeneous absorption efficiencies for the planar model in Fig. 2 and multiplying by the homogeneous sphere result in Fig. 1 gives the dashed curve in Fig. 3, a predicted absorption for the layered sphere. Comparing this predicted absorption to the actual absorption shows that the layering enhancement of the planar model can be applied to the homogeneous sphere solution to predict the absorption in the layered sphere to within 5 percent, both in absorption efficiency at a given frequency and in the location of the resonant peaks.

There are two obvious questions that need to be answered: Why are the geometrical and layering resonances essentially independent in Fig. 1, and why does the planar model predict the layering resonance of the head model with such accuracy?

To answer the first question, consider the geometrical resonance of the head model in Fig. 1. The resonance of the homogeneous sphere is dependent on the radius and constitutive makeup of the sphere. For high loss dielectric bodies of the type considered here, the peak absorption occurs when the ratio of circumference to free-space wavelength ($2\pi a/\lambda = ka$) is about unity. For the homogeneous sphere in Fig. 1, resonance occurs when $ka = 0.94$. Referring to the scale drawing of the sphere in Fig. 1, it is clear that the surface layers represent a small fraction of the total sphere radius (about 10 percent). One would expect then that replacing the outer portion of the homogeneous sphere by a layered segment which on the average has similar dielectric characteristics and whose thickness is much less than a wavelength in the material will have little effect on the geometrical resonant frequency. This is the case as noted in Fig. 1. The layers have an independent resonant frequency, which in this case is approximately four times the geometrical resonant frequency. The frequency at which the layers resonate is a function of their thickness and constitutive parameters. Given the electrical characteristics of the layers, the layering resonant frequency is inversely proportional to the thickness of the layers. The fact that the layering resonant frequency is well removed from the geometrical resonant frequency of the homogeneous sphere accounts for the independence of the two resonances. Numerical calculations show that when the layers are a larger fraction of the sphere radius, i.e., the frequency of surface layer resonance approaches the geometric resonance frequency of the homogeneous sphere, then the geometrical resonance of the inhomogeneous sphere is no longer the same as the geometrical resonance of the homogeneous sphere.

Now consider the second question as to why the planar models can predict both the resonant frequency and enhancement over the homogeneous case for the layered sphere. Looking first at the resonant frequency, we note that in the planar case the incident and transmitted waves are normal to the surface. In the case of the sphere, the only statement that can be made with certainty is that the incident wave is in general not normal to the surface. However, the absorption is due to an internal interaction and the behavior of the fields transmitted into the sphere must be considered.

Snell's law can be used to relate the angle of the transmitted wave to the angle of the incident wave at local regions on the surface. Snell's law for a wave propagating from free space with permittivity ε_o into a region with permittivity ε is given by:

$$\sin\theta_t = \left(\varepsilon_o/\varepsilon\right)^{1/2} \sin\theta_i$$

where θ_i and θ_t are the angles of incidence and transmission, respectively, both angles being measured from the local normal to the surface. The dielectric characteristics of biological tissue are characterized by a relatively large complex permittivity. For example, at the layering resonant frequency of 2.06 GHz, the dielectric constant of the outer skin layer is 47.5 - j11.4. Substituting this into Snell's law for θ_i = 90 degrees (grazing incidence), it is found that the angle of transmission is only 8 degrees from the normal. Since the angle of transmission will be even smaller for other angles of incidence, it is clear that the transmitted wave propagates almost normally into the tissue regardless of the angle of incidence; i.e., the wave transmitted into the sphere interacts with the surface layers in essentially the same manner as it does in the planar model. Therefore, the resonant frequency resulting from this interaction should be the same whether the layers reside on the surface of a sphere or on the surface of a plane.

The fractional enhancement of the absorption due to the layering can best be understood by considering the surface layers as a frequency-dependent impedance matching device. At frequencies well removed from the layering resonant frequency (either far above or far below), the surface impedance of the layered model is the same as for the homogeneous model; i.e., at the lower frequencies the layers are so thin as to have a negligible effect and at very high frequencies the depth of penetration is so low that the transmitted power is all absorbed in the surface skin layer, which has electrical characteristics almost identical to those of the brain material of the homogeneous model. In the region of the layering resonant frequency, an enhanced power transmission occurs, and this enhancement is dependent only on the surface layering configuration, and therefore the fractional enhancement in power transmission will be the same for both spherical and planar models. In the layered planar model, the power transmitted into the innermost layer is completely absorbed. The fractional power absorption enhancement in the sphere can only be the same if all the transmitted power is also absorbed. This will occur if the diameter of the innermost brain material is many skin depths thick. A calculation at the layering resonant frequency of 2.06 GHz shows that the diameter of the inner brain sphere is greater than six skin depths, insuring almost total absorption.

The planar-prediction procedure which has been outlined here for the spherical head model is equally applicable to arbitrary non-spherical bodies, because the mechanism of absorption enhancement depends only on the transmitted wave being nearly perpendicular to the surface layers, a phenomenon which is independent of the body shape. Extensive calculations for other spherical bodies and infinite cylinders have verified the validity of the planar-prediction method. Summarizing:

a. The layering and geometrical absorption resonances for a layered three-dimensional object will be independent if the layering resonant frequency is well above the geometrical resonance; i.e., the surface layers responsible for the layering resonance are a small fraction of the overall size of the object.

b. If the resonances are independent (a condition which can be tested by comparing the geometric resonance of the homogeneous three-dimensional object with the layering resonance of a semi-infinite planar model), then a planar model can be used to predict the absorption layering resonance for nonplanar geometries provided that the complex dielectric constant of the object is large so that the transmitted fields are normal to the layers and the skin depth in the material is small enough that the power transmitted into the interior of the three-dimensional object can be assumed to be completely absorbed.

Note that (a) must be satisfied before (b) can be applied; i.e., the geometric resonance must be independent of the layering because the planar model cannot predict changes in the geometric resonance, only in the layering resonance. Conditions (a) and (b) may appear to be so restrictive as to have little application; however, they are in fact satisfied by most biological models.

Layering Absorption Resonance in Man

It has been shown that a semi-infinite planar model can accurately predict the layering resonance in a nonplanar biological model. The interest here is in determining the effect of layering on the whole-body absorption of EM waves by man. This will be done by using a planar model to determine the absorption enhancement due to surface layering and then applying the resulting enhancement factor to whole-body absorption results previously obtained for a homogeneous prolate spheroidal model of man.

In the numerical calculations which follow, the dielectric characteristics of the various tissue types are taken from [12] for frequencies up to and including 10 GHz. Above 10 GHz, the permittivity and conductivity are based on the characteristics of electrically polarizable molecules [10], modified to provide continuity at 10 GHz with the lower frequency dielectric characteristics.

The surface layers of man in general consist of skin-fat-muscle or skin-fat-muscle-bone-muscle arrangements. The surface layering information required for the multilayered planar model was obtained from published anatomical cross section data [13, 14]. Tissue thicknesses were examined in 79 horizontal cross sections of man. Average thicknesses of the surface layers of skin, fat, muscle, and bone were calculated over the front half of each cross section. It was found that the surface characteristics could be represented by three-layer skin-fat-muscle configurations in 37 of the cross sections, while the remaining 42 cross sections were better represented by a five-layer skin-fat-muscle-bone-muscle configuration. The mean thickness (and standard deviation) of the skin and fat layers for 79 cross sections are 2.25 mm (0.73 mm) and 2.62 mm (1.47 mm), respectively. Corresponding values for the muscle and bone layers for 42 cross sections are 9.74 mm (4.32 mm) and 9.01 mm (4.81 mm), respectively. Calculations similar to those shown in Fig. 2 were made for each of the 79 cross sections. The results were weighted by the fractional frontal surface area which they represented and then averaged to obtain the layered curve in Fig. 4. Note that there is an absorption enhancement over homogeneous muscle tissue of 34 percent at 1.8 GHz and a reduction of 24 percent at 5.7 GHz.

Figure 5 shows the whole-body absorption efficiency for both a homogeneous and a multilayered model of man. The homogeneous result was obtained using a combination of prolate spheroidal and cylindrical models [15]. The specific result shown is for the maximum absorption case which occurs when the model is illuminated broadside by a wave polarized parallel to the long axis of the model. The homogeneous results in [15] were obtained using the dielectric characteristics for a homogenized mixture of fat, bone, and muscle rather than muscle tissue alone. Homogeneous calculations for muscle tissue alone would result in a more accurate multilayered prediction; however, these results are not presently available. The multilayered result was obtained by taking the ratio of the layered to homogeneous absorption efficiencies for the planar model in Fig. 4 and multiplying the layering enhancement factor by the homogeneous result in Fig. 5. Inasmuch as the multilayered data used to generate Fig. 4 were obtained over the front surface of the cross sections of man, the multilayered curve in Fig. 5 is applicable to frontal illumination of a man model. The net effect of the surface layering is generally to increase the absorption in the postresonance region. The layering enhancement at 1.8 GHz and reduction at 5.7 GHz represent the greatest deviation from the homogeneous result. Calculations beyond 10 GHz show that the two results merge when the depth of penetration becomes so small that the total absorption in the multilayered model occurs in the muscle-like skin tissue.

Comparing Fig. 5 to Fig. 1, it is clear that the enhancement of the absorption due to layering is not nearly as great for the whole-body model as it is for the isolated head model. There are two reasons for this. First, for the polarization of the incident wave shown here, the long slender shape of the prolate spheroidal whole-body model results in much greater absorption at the geometrical resonance (absorption efficiency = 4.43) as compared to the spherical head model (absorption efficiency = 1.08). Secondly, the layering enhancement for the whole-body case is much less than for the spherical head model, because of the averaging over many different layering combinations in the whole-body calculations, rather than using a single layering configuration as was done for the spherical head model. If an averaging scheme were used in the head model calculations, a reduction in the layering enhancement would occur there also.

Conclusions

It has been shown that a planar model can accurately predict the layering resonance for a nonplanar geometry. Specifically, results for multilayered and homogeneous semi-infinite planar models determine a layering enhancement factor which can be applied to whole-body absorption results obtained from nonlayered three-dimensional geometries to predict the absorption characteristics of three-dimensional layered geometries. The technique has been used to predict the power absorption characteristics of a multilayered model of man.

Acknowledgment

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Captions for Figures

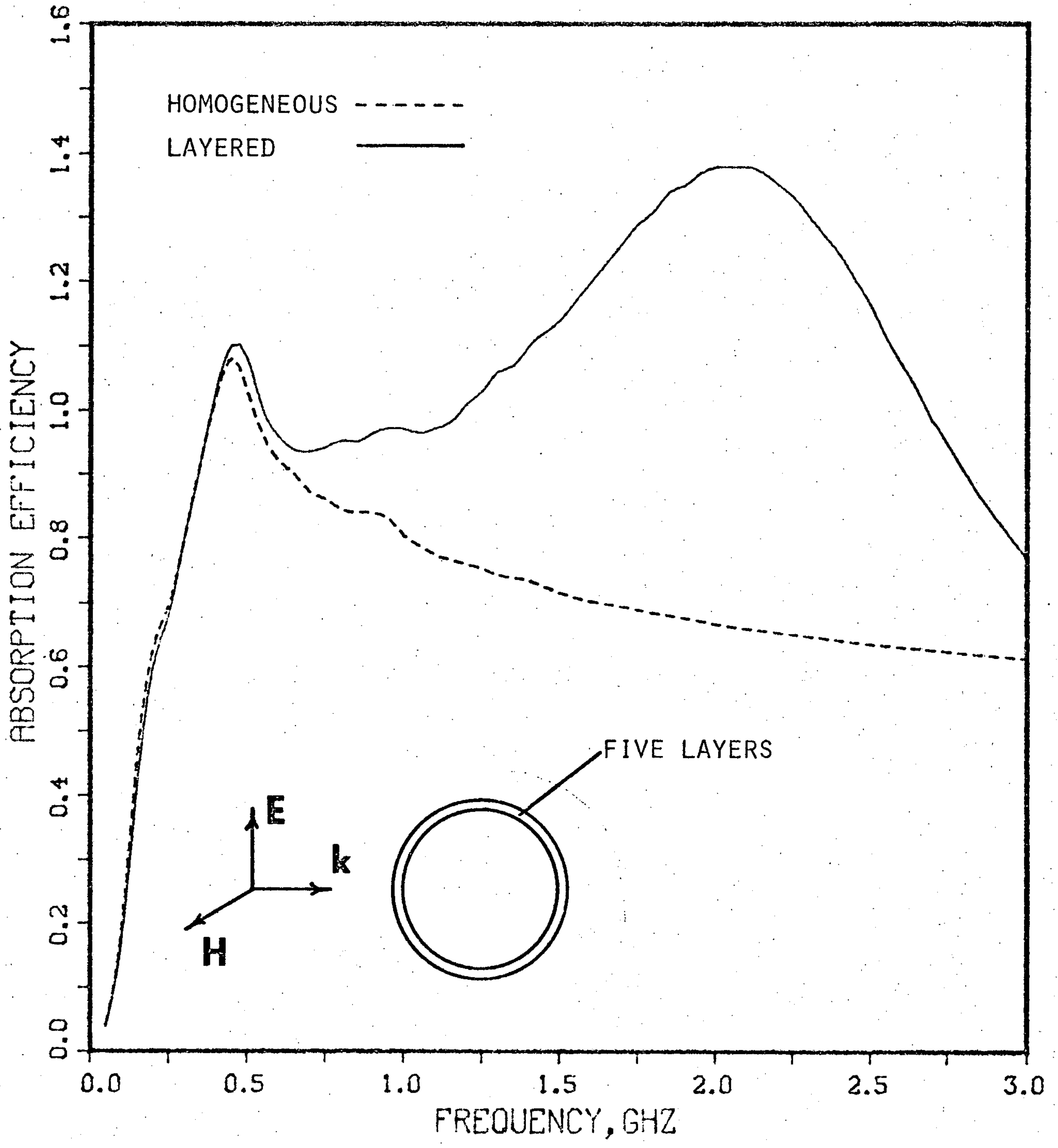
1. Absorption characteristics of the six-layered 10-cm radius spherical head model of Joines and Spiegel [9]. The five outside layers (and thickness) are skin (0.15 cm), fat (0.12 cm), bone (0.43 cm), dura (0.1 cm), and CSF (0.3 cm). The radius of the inner brain sphere is 8.9 cm.

2. Absorption characteristics of a six-layered planar model. The five outside layers are the same as those in Fig. 1. The innermost layer is semi-infinite brain material.

3. Actual and planar predicted absorption characteristics of the six-layered spherical head model of Fig. 1.

4. Predicted whole-body layering resonance in man utilizing a planar model.

5. Whole-body absorption versus frequency for a model of man exposed to a broadside incident plane wave polarized parallel to the long axis of the model. The dashed curve was calculated using homogeneous prolate spheroidal and circular cylindrical models ($a/b = 6.34$, $a = 0.875$ m). The solid curve is the planar-predicted absorption in a corresponding multilayered model of man.



HOMOGENEOUS
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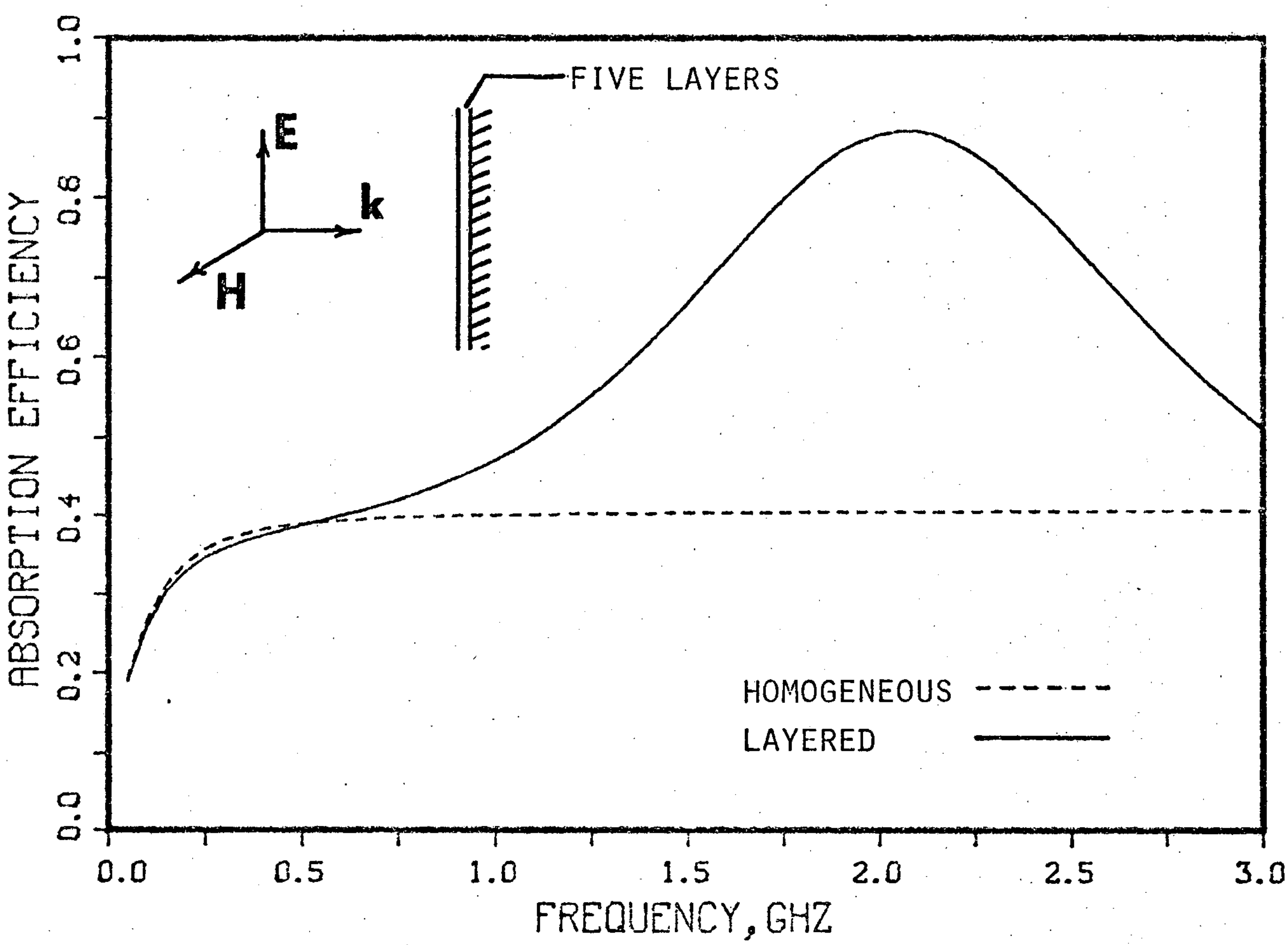
Fig. 1



FIVE LAYERS
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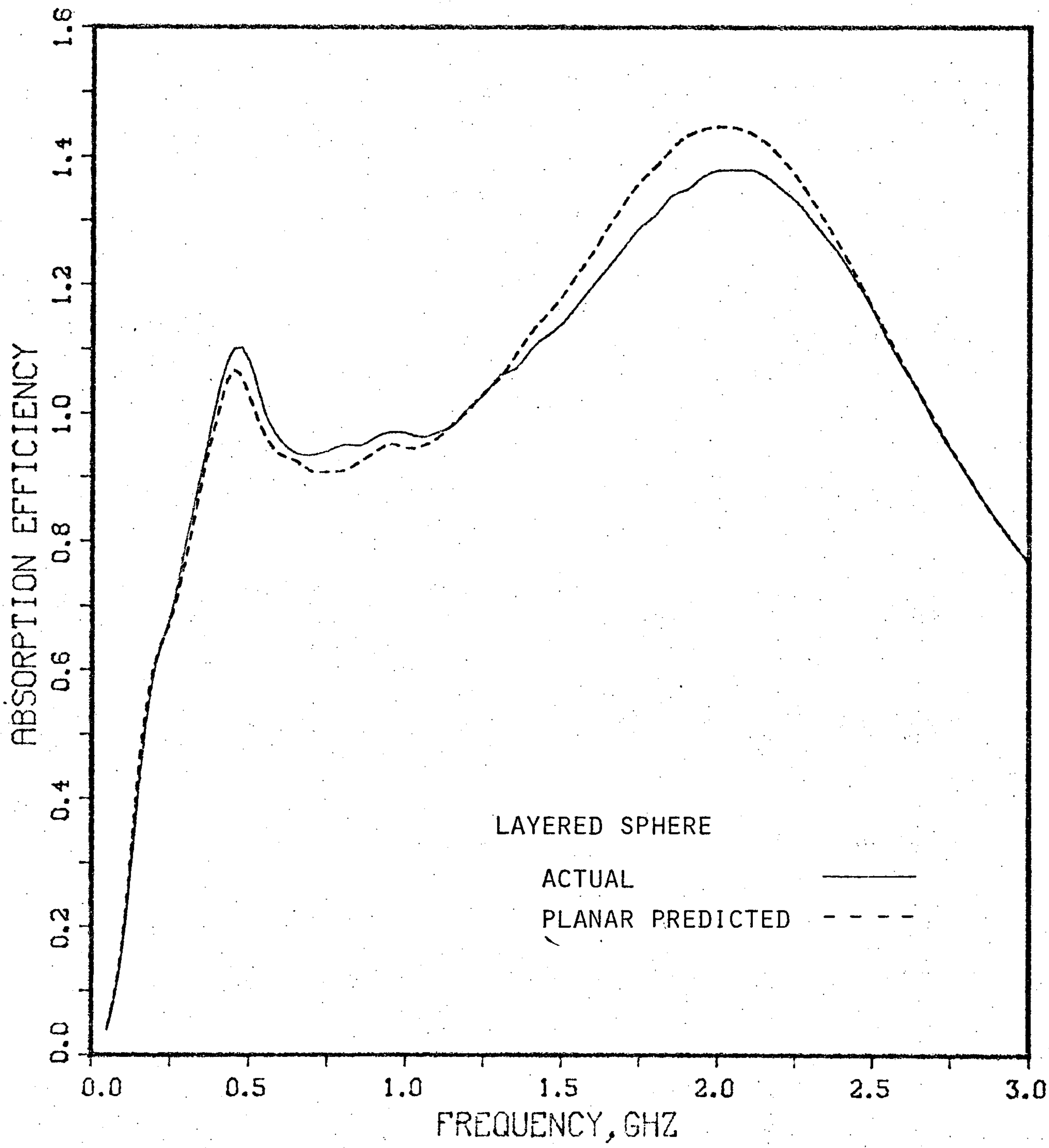
Fig. 2



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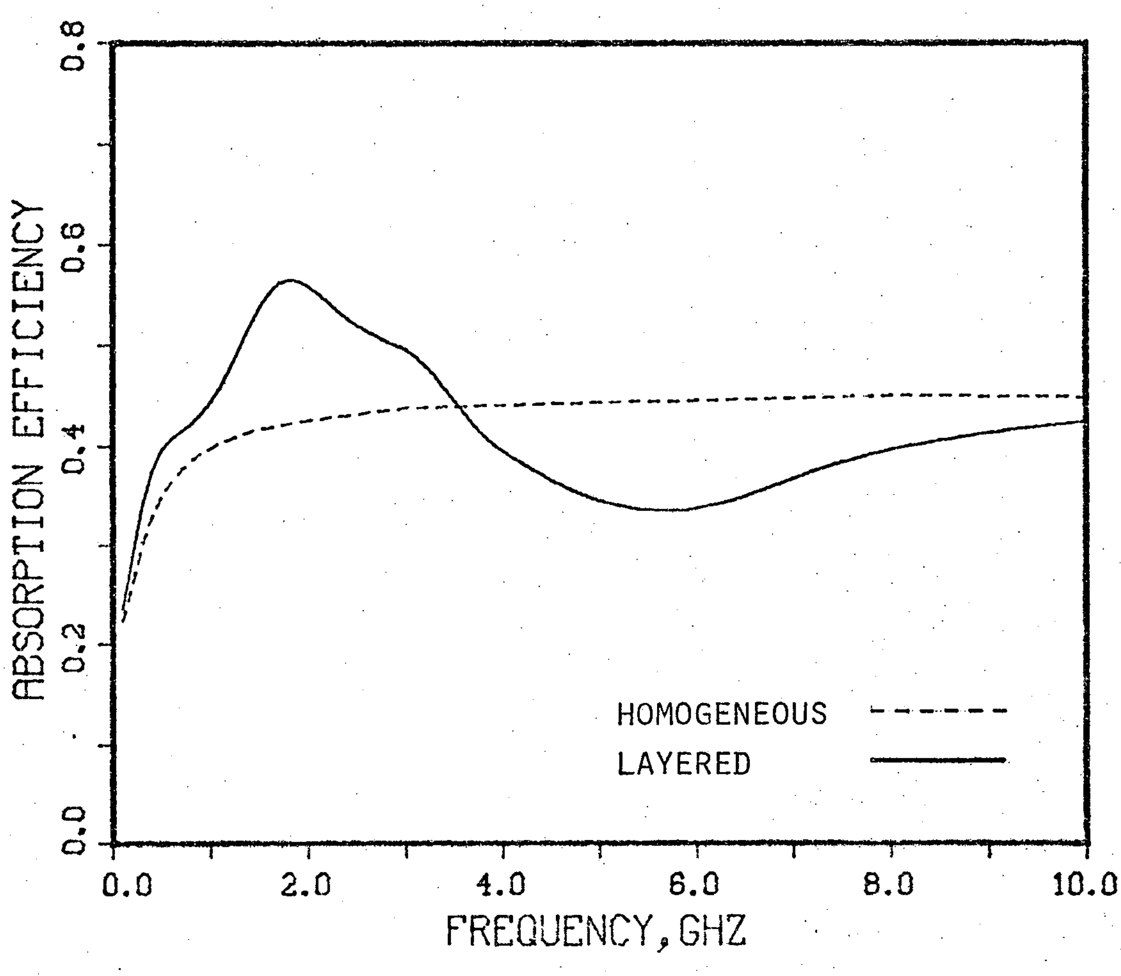
FREQUENCY, GHZ
LAYERED SPHERE
ACTUAL
PLANAR PREDICTED

Fig. 3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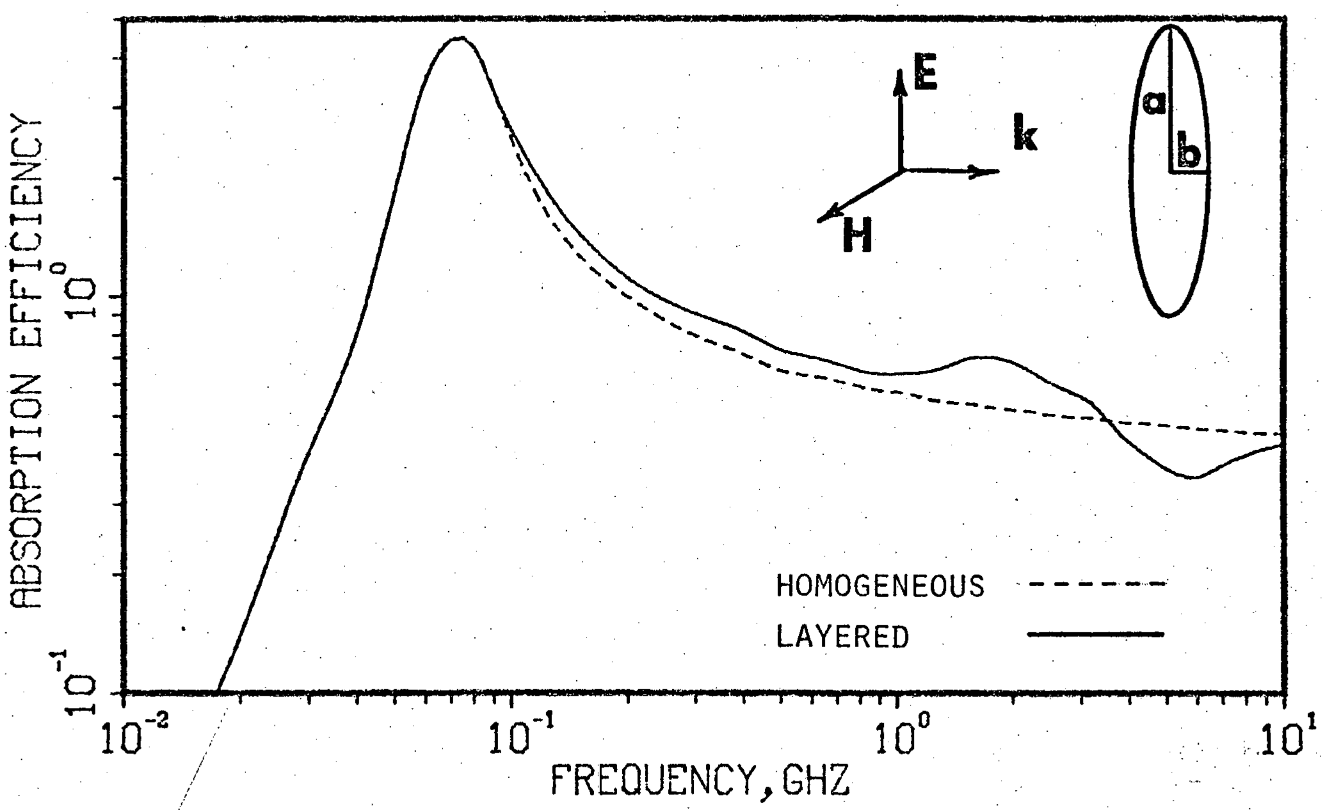
FREQUENCY, GHZ

Figure 4



ABSORPTION EFFICIENCY
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FREQUENCY, GHZ
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a
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HOMOGENEOUS
LAYERED

Figure 5