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THE MICROWAVE PERMEABILITY OF CONDUCTING SPHERICAL SHELLS

HOTON HOW and CARMINE VITTORIA
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
NORTHEASTERN UNIVERSITY, BOSTON, MA

WILLIAM A. SPURGEON
U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
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ABSTRACT

A derivation of an expression for the microwave permeability of a conducting spherical shell analogous to currently available expressions for the permeability of a solid particle is presented in this report. The dependence of the permeability of composites of such particles on shell diameter, thickness, and conductivity for several model systems is explored. A subsequent article will examine the agreement between the models and the experimental data.

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THE PERMEABILITY OF A SPHERICAL SHELL

INTRODUCTION

When an electromagnetic wave interacts with a conductive sphere, it induces an eddy current which is detected as an induced diamagnetism. Equations for the magnetic polarizability of a solid sphere have long been available in the literature[1] and in various texts on electromagnetism, for example, Landau and Lifschitz's Electrodynamics of Continuous Media.[2] From the polarizability, one can develop expressions for the magnetic permeability of a spherical particle and for a composite of such particles in an insulating binder. While difficulties are evident when the calculated composite permeabilities are compared with experimental data, the formulas are at least useful guides to the anticipated behavior of such composites.[3]

Metal coated, insulating spherical shells will show an analogous diamagnetism in their interactions with electromagnetic waves. However, comparable equations for the polarizability and permeability in the literature have not been found, although they may exist. In this report, it shall be shown how such formulas may be derived following the approach in Landau and Lifschitz, and the dependence of the permeability on coating thickness and conductivity, as well as on the diameter of the sphere will be explored.

THE PERMEABILITY OF A SPHERICAL SHELL

Assumptions

A few assumptions are necessary for the formulation. Outside the shell, it is assumed that the wavelength is much greater than the physical dimensions of the particle and that we thus have a quasistatic field without sources ($\vec{\nabla} \times \vec{H} = 0$).

Inside the shell (of conductivity σ), Maxwell's equations and the appropriate wave equations for the magnetic field and current density ($\vec{j}$), assuming a sinusoidal variation in $\vec{H}$, are as follows:

$$\vec{\nabla} \times \vec{E} = \frac{i\,\omega \vec{B}}{c} \tag{1}$$

$$\vec{\nabla} \cdot \vec{B} = 0 = \vec{\nabla} \cdot \vec{D} \tag{2}$$

$$\vec{\nabla} \times \vec{H} = \frac{4\pi \vec{j}}{c} = \frac{4\pi\sigma\vec{E}}{c} \tag{3}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{j} = \frac{4\pi i\,\omega\sigma}{c^2}\,\vec{j} \tag{4}$$

$$\nabla^2 \vec{H} + k^2 \vec{H} = 0, \tag{5}$$

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1. FORD, G. W., and WERNER, S. A. *Helicon Oscillations in a Sphere.* Physical Review, v. 8, 1973, p. 3702-3709.
2. LANDAU, L. D., and LIFSCHITZ, E. M. *Electrodynamics of Continuous Media.* 1st. ed., Addison - Wesley Publishing Company, Inc., Reading, MA, p. 193-194, 1960. Also see 2nd ed., Pergamon Press, New York, 1984, p. 205-206.
3. RUSSELL, N. E., GARLAND, J. C., and TANNER, D. B. *Absorption of Far Infrared Radiation by Random Metal Particle Composites.* Physical Review, v. 32, 1981, p. 632-639.

where $k^2 = \frac{4\pi i \omega \sigma}{c^2}$, or $k = \frac{(1-i)}{\delta}$, where δ, the skin depth, is defined as $\delta = \frac{c}{\sqrt{2\pi\omega\sigma}}$.

It is noted that we have assumed that Ohm's law is valid in the static limit; i.e., the relaxation time for the electrons is much shorter than the inverse of the frequency. This is true for frequencies below the mid-infrared region. Also, the local assumption about Ampere's law presupposes that the mean free path of the electrons within the conductor is small.

Formulation and Solution of the Boundary Value Problem

Consider a spherical shell of inner radius b and outer radius a, with a unit external magnetic field incident, the direction of which can be taken to be along the z axis without loss of generality. Inside the inner conductor (r < b), the field must be well behaved at the origin, and must be a (frequency dependent) constant; therefore:

$$\vec{H}_{\text{int}} = \gamma \, \hat{z} \, , \tag{6}$$

where γ is the internal field strength.

Outside the shell, we expect a dipolar term to be added in opposition to the incident field and this induced dipolar field must vanish at infinity; therefore:

$$\vec{H} = \frac{\alpha}{r^3} \left[3\cos\theta \, \hat{r} - \hat{z} \right] + \hat{z} \, , \tag{7}$$

where α is the magnetic polarizability.

Since the external field is uniform along the z axis, it can only induce dipole terms within the shell, and $\vec{j}$ will have only an azimuthal component. Solutions to Equation 4 for the current density must therefore be of the form

$$\vec{j} = \left[\beta_1 \frac{\sin kr}{r} - \beta_2 \frac{\cos kr}{r} \right] \hat{z} \times \hat{r} \equiv f(r) \, \hat{z} \times \hat{r} \, , \tag{8}$$

from which we can determine H within the shell,

$$\vec{H}_s = \left(\frac{f'}{r} + k^2 f \right) \hat{z} - \left(3\frac{f'}{r} + k^2 f \right) \cos\theta \, \hat{r} , \tag{9}$$

where f′ denotes the derivative of f(r) with respect to r.

Applying the boundary condition that the field be continuous at r = a and r = b, the following equations are obtained:

at r = b,

$$\frac{3\,f'(b)}{b} + k^2\,f(b) = 0, \tag{10}$$

$$\frac{f'(b)}{b} + k^2\,f(b) = \gamma, \tag{11}$$

and at r = a,

$$\frac{3\,f'(a)}{a} + k^2\,f(a) = \frac{-3\,\alpha}{a^3}\,, \tag{12}$$

and

$$\frac{f'(a)}{a} + k^2\,f(a) = \frac{-\alpha}{a^3} + 1\,. \tag{13}$$

For convenience, we introduce the following definitions: B = kb, A = ka, D = a^3, G = $\gamma\, b^3$, S_1 = sinkb, S_2 = sinka, C_1 = coskb, C_2 = coska, T_1 = tankb, T_2 = tanka, and T = tan(A-B). With these definitions, Equations 10-13 become:

$$\beta_1\ [3\ (-\ S_1 + B\ C_1) + B^2\ S_1] + \beta_2\ [3\ (C_1 + B\ S_1) - B^2\ C_1] = 0 \tag{14}$$

$$\beta_1\ [-\ S_1 + B\ C_1 + B^2\ S_1] + \beta 2\ [C_1 + B\ S_1 - B^2\ C_1] = G \tag{15}$$

$$\beta_1\ [3\ (-\ S_2 + A\ C_2) + A^2\ S_2] + \beta_2\ [3\ (C_2 + A\ S_2) - A^2\ C_2] = -\ 3\ \alpha \tag{16}$$

$$\beta_1\ [-\ S_2 + A\ C_2 + A^2\ S_2] + \beta_2\ [C_2 + A\ S_2 - A^2\ C_2] = -\ \alpha + D. \tag{17}$$

With some relatively straightforward algebra (eliminate β_1 and β_2 between the equations and collect terms), one obtains solutions for the polarizability,

$$\alpha = \frac{3}{8\pi}\ \frac{1}{A^2}\,\frac{T\ [(3-A^2)(3-B^2)+9\,A\,B] - 3(A-B)(3+AB)}{T\,(3-B^2)+3B}\,, \tag{18}$$

and for the internal field,

$$\gamma = \frac{3A}{(3-B^2)\sin(A-B) + 3B\cos(A-B)}\,. \tag{19}$$

It can be readily verified that the result for the polarizability reduces to the correct formula for a solid sphere.

The field outside the sphere is that of a uniformly magnetized sphere of permeability μ_p, where

$$\mu_p = \frac{1 + \frac{8\pi\alpha}{3}}{1 - \frac{4\pi\alpha}{3}}\,. \tag{20}$$

Calculated values of μ_p for a 5 micron diameter shell for several thicknesses are shown in Figure 1.

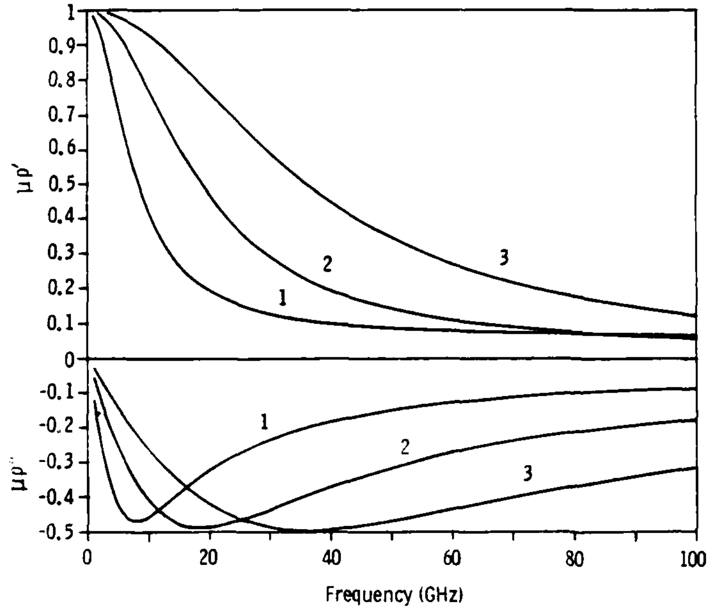


Figure 1. The real and imaginary parts of the permeability as a function of frequency of a copper shell of diameter 5 microns with thicknesses of 0.25 microns (Curves 1), 0.10 microns (Curves 2), and 0.050 microns (Curves 3).

It was hoped that some insight could be gained from the calculated behavior of the internal field. The results of a sample calculation for the real and imaginary parts of the internal field for a 5 micron diameter shell 0.25 microns-thick are shown in Figure 2 (compare with Curves 2 in Figure 1). The imaginary parts of the internal field and of the permeability peak at essentially the same frequency.

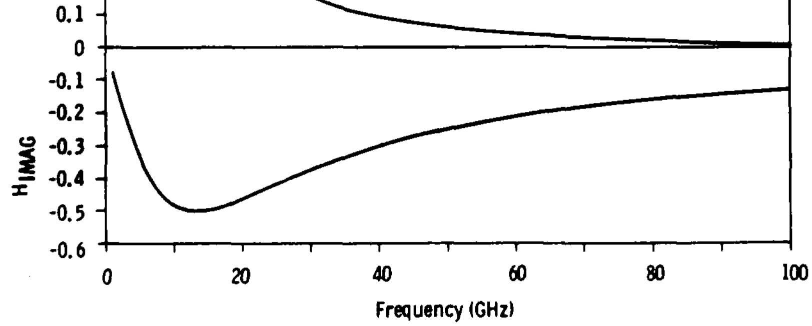


Figure 2. The real and imaginary parts of the internal field as a function of frequency of a 5 micron diameter copper shell of thickness 0.25 microns. Similar behavior is obtained for other shells.

COMPOSITE BEHAVIOR

Many expressions for the dielectric and permeability constants of a composite have appeared in the literature over the years. While all of these seem to have some utility, no one expression seems to be truly adequate for all circumstances.[3-5] One of the most commonly used expressions is that of Maxwell-Garnett, which is used here for want of something more definitive. Also, the interest at the moment is to see how the permeability of the composite depends on the shell thickness and conductivity, and on the diameter of the sphere rather than on the volume fraction of the spherical particles. In this approximation, the composite permeability, μ_c, can be written as:

$$\mu_c = 1 + \frac{3\,f\,(\mu_p - 1)}{(1 - f)\,\mu_p + 2 + f}\,, \tag{21}$$

where f is the volume fraction of particles.

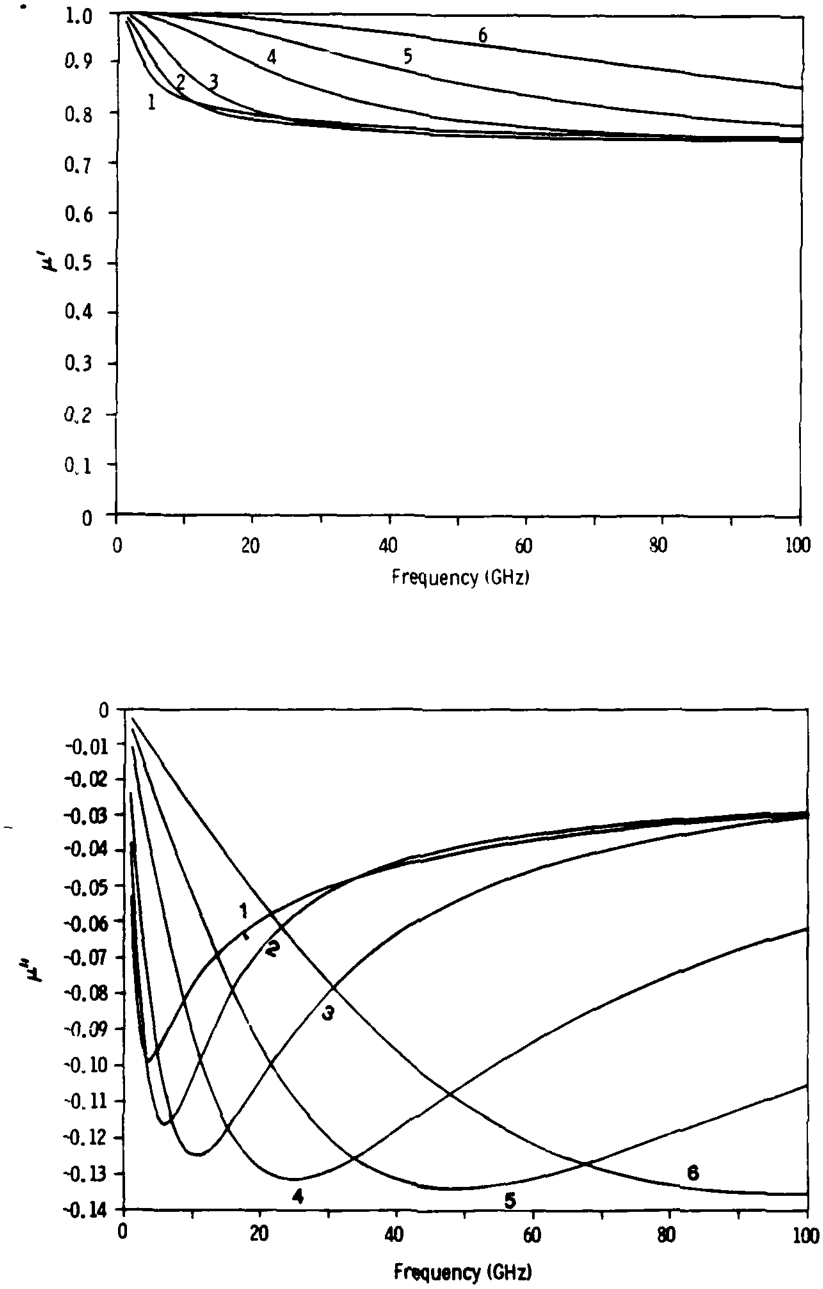
Figures 3A and 3B show, respectively, the real and imaginary parts of the permeability as a function of frequency of a composite of 20 volume-percent of spherical particles in a nonmagnetic binder. The outer radius of the particles was 2.5 microns, and the shell thicknesses are as indicated. The conductivity of the shells was taken to be that of bulk copper. Similar curves, shifted in frequency, are obtained for larger diameter shells and for shells of different conductivity. For example, results for the real and imaginary parts of the permeability of 50 micron diameter copper shell are shown in Figures 4A and 4B, in which a log-linear plot is used to better illustrate the behavior of the imaginary component.

Two interesting features appear in the results for the imaginary component of the permeability. First, the frequency of the peak in μ'' (F_{max}) moves up in frequency as the shell thickness decreases, and, secondly, the peak value of μ'' also increases by as much as 35% over that of a solid particle. A plot of F_{max} as a function of shell thickness for several shell outer diameters is shown in Figure 5. It is noted that there is a region of solid particle-like behavior (in which F_{max} is basically independent of shell thickness) and of shell-like behavior (in which F_{max} varies inversely with shell thickness), and that the transition between them is rather abrupt on the log-log plot. We also find that for a given shell thickness, F_{max} varies inversely with the particle diameter and conductivity. Finally, for very high frequencies, $\alpha = -3/8\,\pi$ and $\mu_p = 0$, which in turn makes a μ_c real constant less than unity.

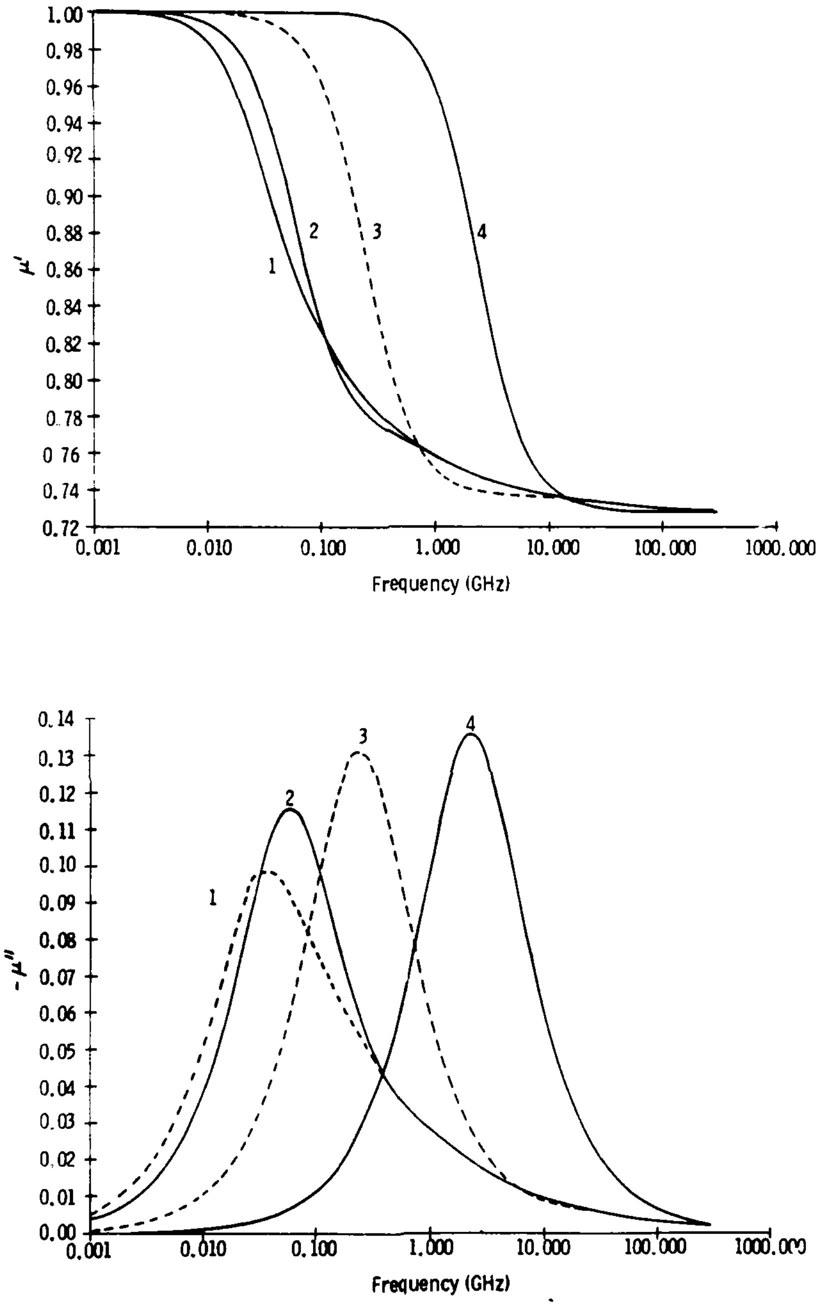
It may be more revealing to show plots of μ_p rather than μ_c; for comparison, a plot of F_{max} for μ_p is included in Figure 5 for a 5 micron diameter particle. The behavior is similar to that of the composite, as expected.

[4] VANBEEK, L. K. H. *Dielectric Behavior of Heterogeneous Systems* in Progress in Dielectrics. J. B. Birks, ed.,Chemical Rubber Company Press, Cleveland, OH, v. 7, 1967, p. 69-114.

[5] HO, Y. S., and KRAMER, J. J. *Microwave Dielectric Properties of Metal Filled Particulate Composites* in Microwave Processing of Materials. W. H. Sutton, H. H. Brooks, and I. J. Chabinsky, ed., Materials Research Society, Pittsburgh, PA, 1988, p. 161-166.



Figures 3A and 3B. The real and imaginary parts of the permeability as a function of frequency of a composite of 20 volume-percent of 5 micron diameter copper shells of thicknesses 2.5 (i.e., a solid sphere), 0.5, 0.25, 0.1, 0.05, and 0.025 microns (Curves 1-6), respectively. The *Maxwell-Garnett expression for the permeability of the* composite was used in the calculations.



Figures 4A and 4B. The real and imaginary parts of the permeability as a function of frequency of a composite of 20 volume-percent of 50 micron diameter copper shells of thicknesses 25 (solid), 5, 1, and 0.1 microns (Curves 1-4), respectively. Note the log-linear plot. The Maxwell-Garnett expression for the permeability of the composite was used in the calculations.

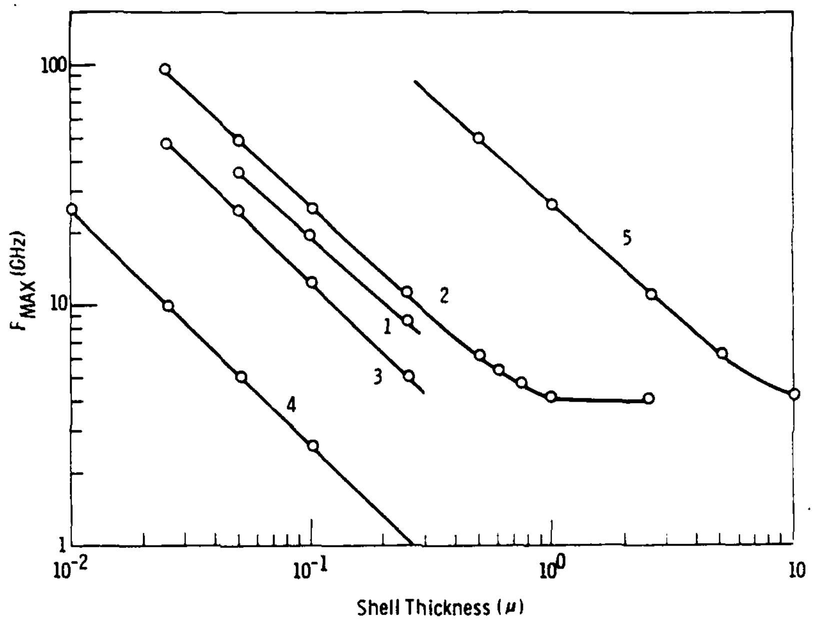


Figure 5. A plot of the frequency of the maximum in μ'' (F_{max}) versus shell thickness for several shell diameters and conductivities. The Maxwell-Garnett expression for the permeability of the composite was used in the calculations.

Curve 1: 5 micron diameter, copper (particle)
Curve 2: 5 micron diameter, copper (composite)
Curve 3: 10 micron diameter, copper (composite)
Curve 4: 50 micron diameter, copper (composite)
Curve 5: 50 micron diameter, material 1/100 as conductive as copper (composite)

The physical reasons for most of these results are not readily evident; one might have expected F_{max} to peak when the shell thickness is roughly equal to the skin depth. For copper, however, the skin depth at 10 GHz is 0.66 microns, whereas F_{max} is about 10 GHz for shell thicknesses of 0.25, 0.1, and 0.025 microns for 5, 10, and 50 micron-diameter shells, respectively. The product of shell diameter and F_{max} is thus nearly constant. Since the shell thickness is (generally) appreciably less than the skin depth, we can approximate the current in the shell, I, as being uniform within the shell, and equal to $2\pi rtj$, where r is the radius, and t the thickness of the shell. The current in the shell and the internal field must be linearly related, and from inspection we find that the imaginary part of the internal field varies linearly with frequency at low frequencies (see Figure 2). Thus,

$$I_{imag} = 2\pi r t \eta \sigma F, \tag{22}$$

where η is a constant and the conductivity dependence has been made explicit. At very high frequencies, the imaginary part of the current must drop to zero as the penetration depth decreases, and I_{imag} will therefore peak at some intermediate value, F_{max}. It is expected that the maximum in I_{imag} ($2\pi rt\eta\sigma$ F_{max}) would be a constant, from which the dependence of F_{max} on σ, r, and t follows directly.

It is further noted that expressions for α, μ_p and μ_c are mathematically linear in A - B, and, hence, in shell thickness for small shell thicknesses.

Other models for the dielectric constant of a mixture of spherical particles in a matrix could also be extended to the permeability. For comparison purposes, Figures 6A and 6B show the expected behavior for a composite of 20 volume percent particles calculated from the Maxwell-Garnett theory (Curve 1), from effective medium theory (Curve 2), for which is given by

$$\frac{f\,(\mu_p - \mu_c)}{\mu_p + 2\,\mu_c} + (1-f)\,\frac{(1 - \mu_c)}{1 + 2\,\mu_c} = 0\,, \tag{23}$$

and from a model developed independently by Looyenga and by Landau and Lifschitz (Curve 3) for which

$$\mu_c = [\,1 + (\mu_p{}^{1/3} - 1)\,]^{3}\,. \tag{24}$$

The real part of the permeability (see Figure 6A) is pretty much the same in the models, but the imaginary part (see Figure 6B) is quite different at high frequencies.

It is quite possible that none of these model formulas will adequately describe the permeability of the composite. This point will have to await experimental verification (which will be the subject of a subsequent article). However, we do expect the general features described above to be observed.

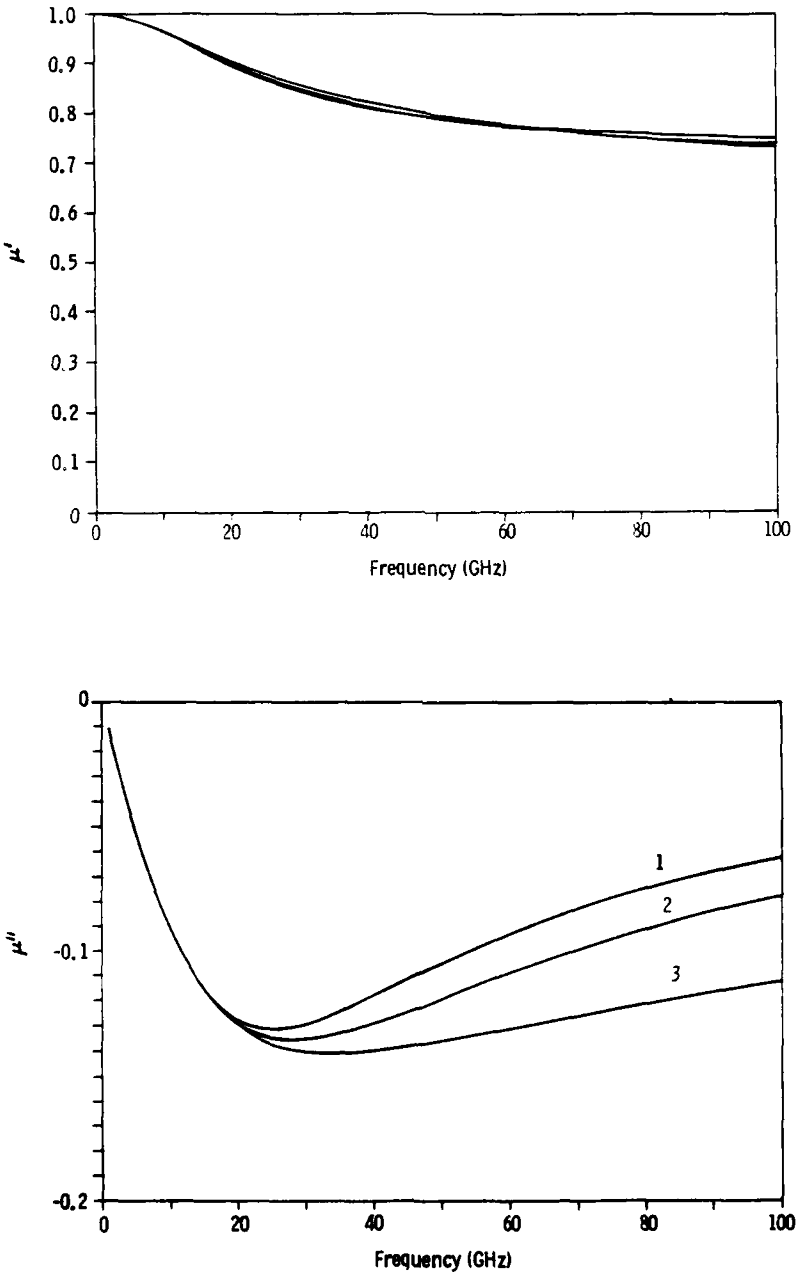
The dielectric constant of a composite of metal particles, or shells, in an insulating binder is also of interest. The Maxwell-Garnett expression for the dielectric constant of such a composite, ε_c, simplifies to

$$\varepsilon_c = \varepsilon_b \left(\frac{1 + 2f}{1 - f} \right), \tag{25}$$

where ε_c is the dielectric constant of the binder, since the dielectric constant of the metal particle is extremely large. This expression seems to generally underestimate the dielectric constant and such microstructural variables as particle size and dispersion, as well as material parameters (particle type, conductivity, etc.), are ignored, as are all effects due to particle-particle contact. Ho and Kramer[5] present a modified expression for the dielectric constant:

$$\varepsilon_c = \varepsilon_b \left[\frac{(1 - \langle h \rangle)\,(1 - f) + \langle h \rangle\, f}{(1 - f)^2\,(1 - \langle h \rangle)} \right], \tag{26}$$

in which <h> is an average particulate shape factor, which serves as a measure of particle contact or chain formation, which is obtained by an independent microstructural analysis. For isolated spherical particles, <h> = 2/3, and approaches 1 for a long chain of contacting particles. Their formula gives a generally improved fit to their data for the real part of the dielectric constant for their low loss samples.



Figures 6A and 6B. The real (6A) and imaginary (6B) parts of the permeability as a function of frequency for a composite of 20 volume-percent of 50 micron diameter, 0.1 micron-thick spherical shells calculated using different models for the permeability of the composite (Curve 1, Maxwell-Garnett; Curve 2, Effective Medium Approximation; Curve 3, Landau and Lifschitz - Looyenga). Mathematical expressions for the permeability are given in the text.

Although the Ho-Kramer article does represent a definite improvement in the theory of the electromagnetic properties of metal-filled particulate composites, it is clear that more improvement is desirable. It is noted that Ho and Kramer do not present data for the permeability of their samples; this is largely because they do not understand their results as yet.*

CONCLUSIONS

An expression for the permeability of a conducting spherical shell which should be accurate as far as classical electromagnetic theory is concerned has been derived. We have also explored the calculated behavior of composites of such particles in an insulating binder using various theories for the permeability of the composite. A subsequent article will address a comparison of the calculated results with experimental data.

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*J. J. Kramer, private communication, July, 1989.

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U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
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Hoton How, William A. Spurgeon, and
Carmine Vittoria

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