Tailoring The Microwave Permittivity And Permeability Of Composite Materials

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ABSTRACT

The microwave permittivity(ε_r) and permeability(μ_r) of composite materials are tailored by adding various loading agents to a host epoxy resin and are subsequently modeled using the Maxwell Garnett theory and second order polynomials. With the addition of manganese zinc ferrite, strontium ferrite, nickel zinc ferrite, barium tetratitanate and graphite powder, materials with values of ε', ε'', μ', μ'' as high as 22, 5, 2.5 and 1.7 have been obtained. Permittivity and permeability data are calculated at 2.0245 GHz from reflection and transmission measurements performed in a 7 mm coaxial test line. The Maxwell Garnett(MG) theory successfully models ε_r if the filling factor is less than 0.30 and the ratio $|\varepsilon_1|$(host)/$|\varepsilon_2|$(powder) is greater than 0.04. As this ratio decreases, the MG theory is shown to be independent of ε_2 and second order polynomials are used to effectively model the dielectric constant. Polynomials are also used for the ferrite composites because it was determined that the MG theory was unable to model μ_r. This deficiency is attributed to the difference of domain structures that exist in powdered and sintered ferrites.

I. INTRODUCTION

The idea of theoretically predicting the permittivity of a composite material has been a source of continuing interest since the late 1800's [1-12]. Dielectric specific materials are required for microwave components such as isolators, circulators, phase shifters, lenses and dielectric waveguides. Commercially available materials often limit the design of these devices including frequency selective surfaces such as bandpass and lowpass filters as well as radar absorbing materials(RAM). In an effort to rectify this situation, the authors have constructed theoretical models to predict ε_r by approaching the problem with the fundamental equations of electrodynamics, scattering methods or with pure mathematical models [13]. Despite these efforts, a universal theory capable of theoretically predict the permittivity of a composite material has not been established.

The MG theory presented in 1904 by J. C. Maxwell Garnett is still considered to be the fundamental theory for predicting the permittivity of a composite material [2,3]. Although the MG theory has been used extensively to study the complex index of refraction of metal-insulator composites at optical frequencies [14-41], little data regarding the microwave permittivity of composite materials exists in literature [35-42]. The MG theory has not been subjected to scrutiny at microwave frequencies and has not been tested when the

permittivity of the powder is substantially larger than that of the host medium. Permeability data on composite materials at microwave frequencies is even more rare [89,92]. Despite this lack of experimental data, it is often assumed that the MG theory is capable of modeling the permeability of composite materials. Consequently, the validity of this statement has never been proven and has always been taken for granted. In order to effectively fabricate new composite materials with tailorable optical properties, precise theoretical predictions must be established. Therefore the ability of the Maxwell Garnett theory to model the permittivity and permeability of composite materials is investigated and discussed.

II. THEORY

The Maxwell Garnett (MG) theory is the most popular method employed for modeling the permittivity of two-component composite materials. The permittivity of the composite is defined only in terms of the permittivities of the components and the volume percentage of the loading agent. The composite is assumed to consist of spherical particles with a mean radius α, uniformly distributed throughout a host medium. The polarization in each sphere is assumed to arise only from the presence of the external field and multipole effects due to neighboring particles are not considered. Although the MG theory produces an equation for the permittivity of a composite material, the same formalism can be used to derive an analogous expression for the material's permeability.

The task of determining the electric field everywhere inside the composite is simplified by using the electric fields inside and outside a single sphere to represent the actual fields in the material [43]. Consider a sphere of permittivity ε_2 and radius α surrounded by a host medium of permittivity ε_1. The sphere is subject to a uniform, constant, external electric field $\vec{E}_{ext} = E_0\hat{z}$. There is no free charge density in either the host medium(region 1) or the sphere(region 2) so the electric field in these regions can be calculated from the following scalar potentials satisfying Laplace's equation

$$\Phi_1 = \sum_{l=0}^{\infty} \left[A_l r^l + \frac{B_l}{r^{l+1}} \right] P_l(\cos\theta) \tag{2.1}$$

$$\Phi_2 = \sum_{l=0}^{\infty} \left[C_l r^l + \frac{D_l}{r^{l+1}} \right] P_l(\cos\theta).$$

The absence of any free charge at the center of the sphere requires the coefficients $B_l = 0$ because the potential Φ_2 must be finite at $r = 0$. At large distances from the sphere($r = \infty$) the electric field is not disturbed by the presence of the sphere and is therefore equal to the incident field. This dictates all $C_l = 0$ except for $C_1 = -E_0$. The displacement and electric fields produced by these potentials must also satisfy the following boundary conditions at the surface of the sphere($r = \alpha$)

$$\left(\overset{\vee}{D}_2 - \overset{\vee}{D}_1\right)\hat{n} = 0 \qquad (2.2)$$
$$\left(\overset{\vee}{E}_2 - \overset{\vee}{E}_1\right)\times\hat{n} = 0$$

because the fields at the boundary are finite and no free surface charge density exists. After applying these boundary conditions and equating the coefficients of the Legendre polynomials, the scalar potentials and electric fields in regions (1) and (2) are given by

$$\Phi_2 = -\frac{3\varepsilon_1 E_0}{\varepsilon_2 + 2\varepsilon_1} r\cos\theta \qquad (2.3)$$
$$\Phi_1 = -E_0 r\cos\theta + \frac{\alpha^3 E_0\left(\varepsilon_2 - \varepsilon_1\right)}{r^3\left(\varepsilon_2 + 2\varepsilon_1\right)}\cos\theta$$
$$\overset{\vee}{E}_2 = \frac{3E_0\varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}\left(\cos\theta\hat{r} - \sin\theta\hat{\theta}\right) = \frac{3E_0\varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}\hat{z}$$
$$\overset{\vee}{E}_1 = E_0\left(\cos\theta\hat{r} - \sin\theta\hat{\theta}\right) + \frac{E_0\alpha^3\left(\varepsilon_2 - \varepsilon_1\right)}{r^3\left(\varepsilon_2 + 2\varepsilon_1\right)}\left(2\cos\theta\hat{r} - \sin\theta\hat{\theta}\right).$$

Equation (2.3) indicates the electric field inside the sphere is constant and in the direction of the applied field. However, the field inside the host medium is not constant and is equal to the incident field plus an additional field which would be produced by an electric dipole situated at the origin of the sphere with dipole moment

$$p = \frac{E_0\alpha^3\left(\varepsilon_2 - \varepsilon_1\right)}{\left(\varepsilon_2 + 2\varepsilon_1\right)}. \qquad (2.4)$$

The dipole field exhibits a $1/r^3$ dependence so it's contribution to the net electric field is significant only at distances close to the sphere. Therefore, the dipole term is considered negligible and excluded from the expression for $\overset{\vee}{E}_1$. As a result, the electric field in the host medium is equal to the incident field.

The MG theory utilizes the results of equation (2.3) to define an average electric, displacement and polarization field given by

$$\overset{\vee}{D}_{avg} = f\overset{\vee}{D}_2 + (1-f)\overset{\vee}{D}_1 \qquad (2.5)$$
$$\overset{\vee}{E}_{avg} = f\overset{\vee}{E}_2 + (1-f)\overset{\vee}{E}_1$$
$$\overset{\vee}{P}_{avg} = \left(\varepsilon_{eff} - 1\right)\overset{\vee}{E}_{avg} = f\left(\varepsilon_2 - 1\right)\overset{\vee}{E}_2 + (1-f)\left(\varepsilon_1 - 1\right)\overset{\vee}{E}_1.$$

The volume filling factor f, is equal to the volume ratio of spheres to the host medium and ε_{eff} is the effective permittivity of the composite material. Solving for ε_{eff} yields the following relation

$$\varepsilon_{eff} = \frac{\varepsilon_2 f + \varepsilon_1 (1-f)\frac{\breve{E}_1}{\breve{E}_2}}{f + (1-f)\frac{\breve{E}_1}{\breve{E}_2}}. \qquad (2.6)$$

The permittivity of the composite material is easily calculated(not a tensor quantity) provided a scalar relationship exists between $\breve{E}_2$ and $\breve{E}_1$. According to equation (2.3) this is not possible unless the dipole term is neglected from the expression for $\breve{E}_1$. The effective permittivity is then simply

$$\varepsilon_{eff} = \varepsilon_1 \frac{2\varepsilon_1(1-f) + \varepsilon_2(1+2f)}{\varepsilon_1(2+f) + \varepsilon_2(1-f)}. \qquad (2.7)$$

The same equation is obtained for the effective permeability with each ε_r replaced with it's corresponding μ_r.

Although the simplicity of (2.7) is convenient, it's validity is limited by the assumptions made in it's derivation. A noteworthy consequence is that (2.7) is not symmetric upon interchange of the components, i.e. $\varepsilon_{eff}(\varepsilon_1, \varepsilon_2) \neq \varepsilon_{eff}(\varepsilon_2, \varepsilon_1)$ when f=0.5. The neglect of the dipole field implies the host medium is lossless and that each particle is exposed to the same electric field. The electric fields in the material are altered by the presence of other particles which indicates that even if the dipole field is included, (2.7) does not give an exact representation of the fields in the material. As interparticle distances become smaller(increasing f), multipole effects become more significant. Consequently, the MG theory is not expected to model ε'', μ'', and is limited to theoretically modeling ε' and μ' at low values of f when interparticle spacing is large.

Upon further examination of equation (2.7), it has been discovered that the MG theory breaks down for all f when the permittivity(or permeability) of the loading agent is much larger than that of the host medium. By factoring out ε_2 and applying the condition $\varepsilon_2 >> \varepsilon_1$, (2.7) becomes

$$\varepsilon_{eff} \approx \frac{\varepsilon_1(1+2f)}{(1-f)}. \qquad (2.8)$$

Equation (2.8) represents a physically unrealistic situation which predicts the same ε_{eff} for a host resin loaded with particles of permittivity $\varepsilon_2 = 1000$ or $\varepsilon_2 = 10{,}000$. This phenomenon stems from all of the assumptions made in the MG theory and shows up as an artifact of the mathematics involved in the derivation of equation (2.7). Due to the fact $\varepsilon_2 >> \varepsilon_1$ is a relative condition, it is expected that agreement between theoretical and experimental data will gradually diminish as this criterion is met. Therefore, existence of the limiting form of the MG theory uncovered in (2.8) must be proven by increasing ε_2 until the criterion $\varepsilon_2 >> \varepsilon_1$ is established and exceeded.

III. EXPERIMENT

The composite materials are fabricated by loading powdered magnetic and dielectric materials into C-1504, a rigid, two-component, urethane casting resin manufactured by Smooth On, Inc. [44]. The permittivity and permeability of the host resin are tailored using nickel zinc ferrite (TT2-111), manganese zinc ferrite ($Mn_{0.5}Zn_{0.5}Fe_2O_4$), strontium ferrite ($SrFe_{12}O_{19}$), barium tetratitanate($BaTi_4O_9$, aka D-38) and graphite powders. Precise filling factors are calculated using the formula

$$f = \frac{vol.\ powder}{vol.\ powder + vol.\ host} = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{m_h}{1.12\left(g/cm^3\right)}} \tag{3.1}$$

where m_p, ρ_p are the mass and density of the powder. Each powder exhibits different wetting properties and is responsible for the maximum filling factors that can be achieved. Torroidal samples are machined from bulk materials to fit into a 7 mm coaxial test line for measurement.

An HP8510B network analyzer is used to perform transmission and reflection measurements on these samples from 0.05 to 18 GHz. Vector, error-corrected data is obtained by calibrating the network analyzer using a TRL, Full 2-Port vector calibration model. Data is obtained by performing 256 measurements at 401 equally spaced frequency points. In order to maintain measurement repeatability, the synthesized sweeper is configured to phase-lock at each desired frequency. The data acquisition process is automated using an HPIB-MAC bus in conjunction with a Macintosh computer running Labview®3.0 software.

The complex permittivity and permeability of the composite materials are calculated from measured s-parameters using one of two algorithms. The Nicholson-Ross-Weir algorithm is a reference plane dependent solution containing explicit equations for μ_r and ε_r and is used for the ferrite composites [45-47]. The Baker-Jarvis algorithm is a reference plane independent solution which forces $\mu_r = 1$ and utilizes the Newton-Raphson iteration technique to calculate the permittivity of dielectric materials [48]. The possible ambiguity that can arise from this method is easily resolved by comparing the measured s-parameters to those calculated using the results of the numerical analysis.

IV. PERMITTIVITY RESULTS

Reflection and transmission measurements performed on bulk materials were used to determine the permittivity of the loading agents and the host medium. The casting resin C-1504 exhibits a relatively constant ε' and an ε'' increasing slightly with frequency over the measured range(45 MHz-18 GHz). The 2.0245 GHz dielectric constant is 2.97-i0.14. The

manufacturer reported values of ($\varepsilon' = 12.5 \pm 10\%$, $\tan\delta < 0.001$) for TT2-111 and ($\varepsilon' = 37 \pm 5\%$, $\tan\delta < 0.0005$) for D-38 are substantiated with measurements performed in the airline [13, 49]. However, large permittivities and air gaps prevented the dielectric constant from being calculated for strontium ferrite, manganese zinc ferrite and graphite. Comparison of composite data does indicate that strontium ferrite has an $\varepsilon' \approx 40$ and manganese zinc ferrite as well as graphite have permittivities over 100 [13].

These composites consisting of powders with permittivities ranging from 12 to well over 100 were used to determine the effectiveness of the MG theory. It's limiting form presented in equation (2.8) is based upon the relative condition $\varepsilon_2 >> \varepsilon_1$, so agreement with theory is expected to become worse as ε_2 increases. The MG theory most successfully modeled ε' for the TT2-111 and D-38 composites shown in Figure 1. The deviation from theory is less than 4% for the TT2-111 composites and obtains a maximum of

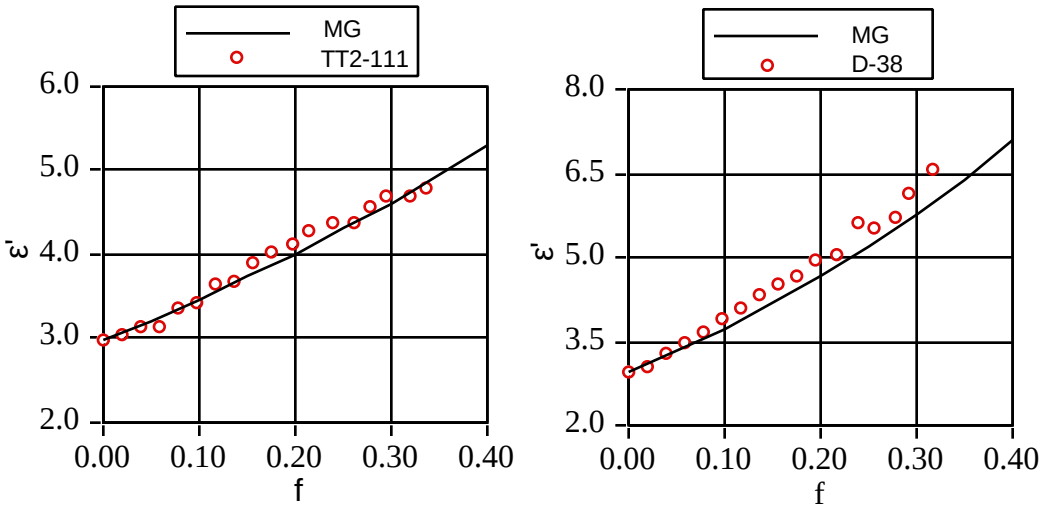


Figure 1: ε' as a function of f for TT2-111 and D-38 loaded C-1504.

10% at f=0.32 for the D-38 materials. While theory readily predicts ε' for the TT2-111 samples, the results consistently exceed the calculated values for the D-38 composites. This indicates that equation (2.7) has already started to breakdown and is not capable of effectively modeling ε' when the dielectric constant of the powder is increased to 37. The mathematical criterion necessary to validate the existence of equation (2.8) is almost established.

Dionne et. al. calculated ε' for TiO_2 (anatase $\varepsilon' = 48$, rutile $\varepsilon' = 100$) loaded paraffin wax as a function of f at 10 GHz [50]. Their permittivity data is displayed along with equations (2.7) and (2.8) in Figure 2. The

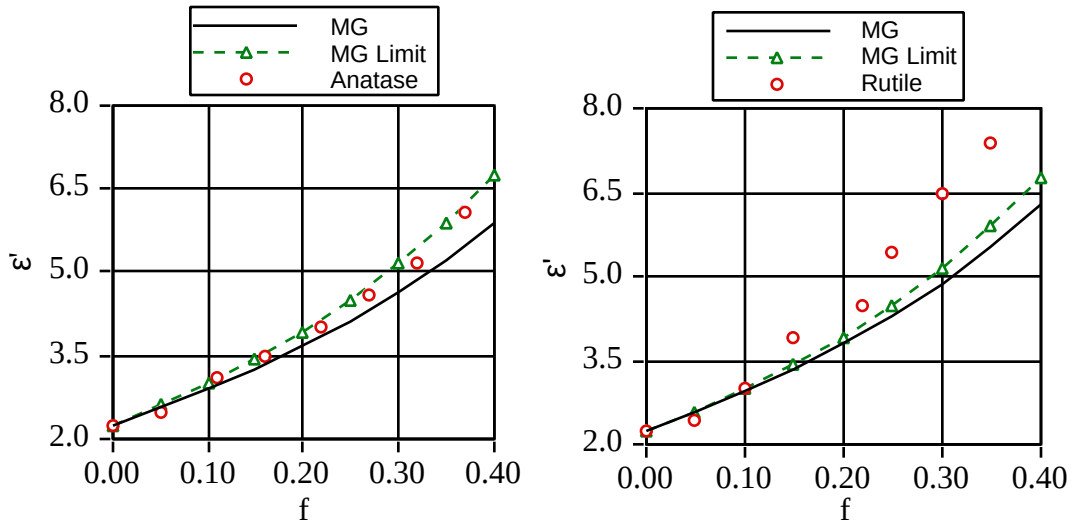


Figure 2: ε' as a function of f for TiO_2 loaded paraffin wax [50].

permittivity ratio $|\varepsilon_1 / \varepsilon_2|$ is 0.047 for anatase and 0.022 for rutile loaded paraffin wax. Both the anatase and rutile data exceed the results of (2.7), while only rutile surpasses the limiting form given by (2.8). This indicates that the necessary criterion required to establish the limiting form of the MG theory occurs when $\varepsilon_1/\varepsilon_2 \approx 0.04$. Increasing ε_2 beyond this point will not have any effect on the quantities predicted by the MG theory. Dionne's results also illustrate that graphite and manganese zinc ferrite have permittivities larger than 100. Therefore, the ε_r of the composites containing these powders exceed the limiting form of equation (2.8) even further than the rutile data. The gradual process of establishing and exceeding the criterion($\varepsilon_2 >> \varepsilon_1$) necessary to validate (2.8) is summarized in Figure 3.

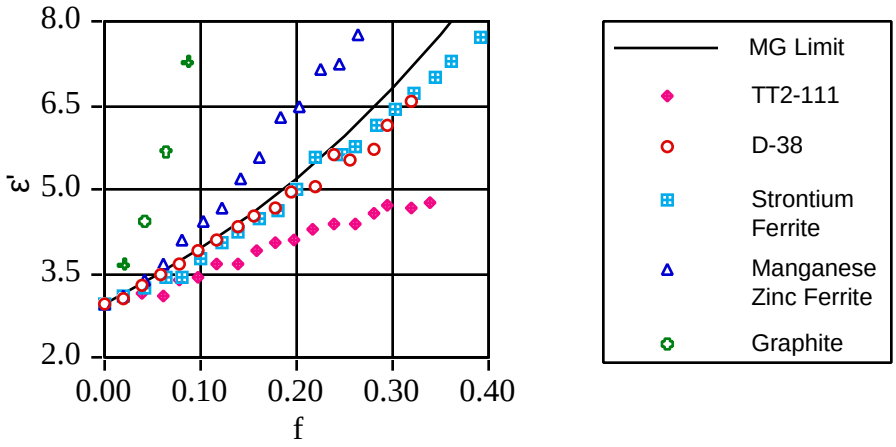


Figure 3: Comparison of composite ε' with the limit of the MG theory.

The MG theory, as expected, was unable to model ε" for any of the composite materials. In fact, theory predicts ε" values higher than that of

the host material as f increases for both the TT2-111 and D-38 composites. See Figure 4. This is unrealistic since both of these powders posses an ε"

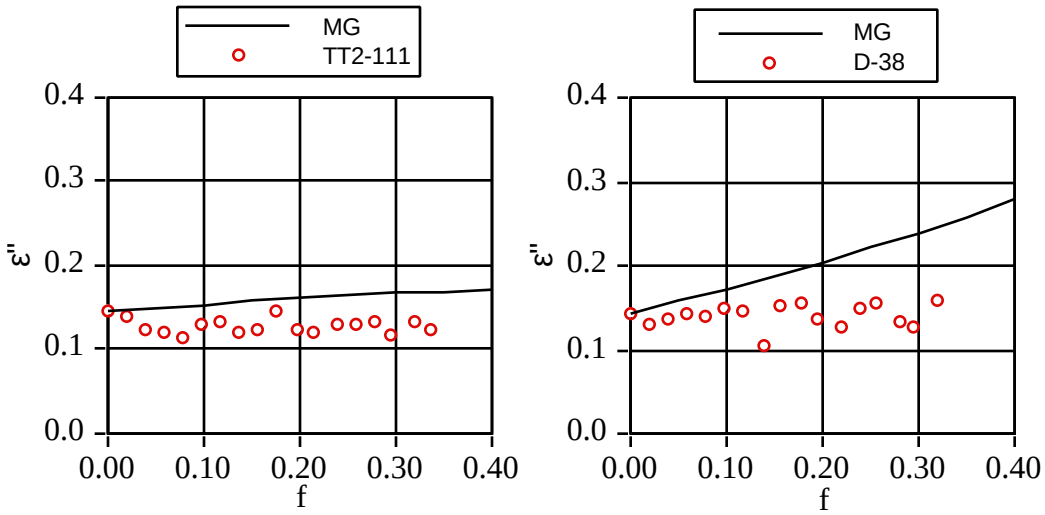


Figure 4: ε" as a function of f for TT2-111 and D-38 loaded C-1504.

lower than that of C-1504. This phenomena is purely an artifact of the mathematics involved in the derivation of (2.7) and is illustrated in Figure 5. Permittivity data is generated as a function of f for various loading agents with the same ε"=0.02 and different values of ε'. The rise in composite ε" data becomes steeper as the ε' of the powder is increased. The consistency of the MG theory requires ε"=0.02 at f=1, making it necessary for the theory to mathematically predict the sudden drop experienced in the ε" data. From these results it can be stated that the theory is not capable of modeling ε" data when ε" of the loading agent is less than that of the host medium.

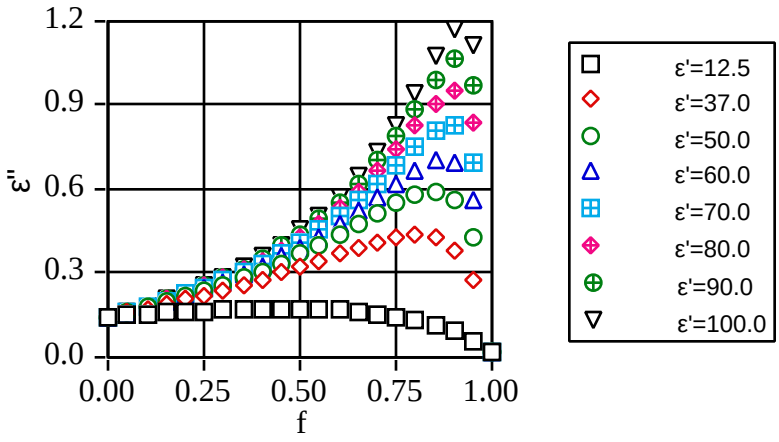
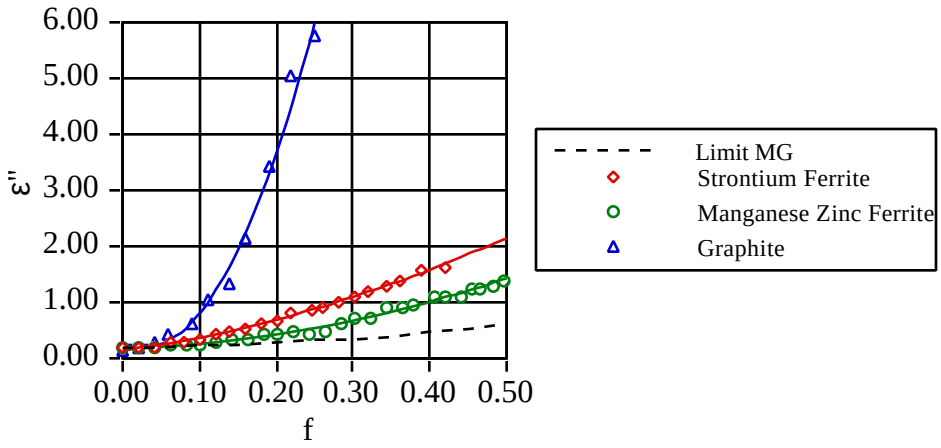


Figure 5. The phenomena in ε" predicted by the MG theory as the powder's ε" is held constant and it's ε' is increased.

The remaining ε" data for the strontium ferrite, manganese zinc ferrite and graphite composite materials could not be analyzed using equation (2.7), due to the lack of permittivity data on the sintered bulk materials. However, according to Figure 6, this is irrelevant since all three curves lie above the maximum values allowed by equation (2.8). Although, this data can not be predicted using the MG theory, it can be effectively modeled using second-order polynomials(solid lines through data). These polynomials are dependent only on the filling factor f and are purely mathematical models. It is also necessary to use these second-order polynomials to model the ε' data for these composite materials. A summary of these equations is also given in Figure 6. The variables A, B, C are the coefficients of the powers of f, and r^2 is the coefficient of determination. It is a measure of well the function fits the data where r^2=1 is an ideal fit.



COMPOSITES(ε')	A	B	C	r^2
$SrFe_{12}O_{19}$	8.094	9.266	2.834	0.995
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	35.594	11.273	2.851	0.994
Graphite	216.636	37.147	2.695	0.998

COMPOSITES(ε")	A	B	C	r^2
$SrFe_{12}O_{19}$	4.319	1.858	0.110	0.998
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	3.940	0.528	0.137	0.991
Graphite	115.613	-5.738	0.212	0.988

Figure 6. ε" as a function of f vs. the limiting form of the MG theory for strontium ferrite, manganese zinc ferrite and graphite loaded C-1504. Second-order polynomials (ε', $\varepsilon'' = Af^2 + Bf + C$) used to theoretically predict the complex dielectric constant for these composite materials.

V. PERMEABILITY RESULTS

It is often stated the MG theory can be extended to model the permeability of composite materials without verifying this idea with experimental data. The most important and frequently overlooked assumption made in it's derivation is that the permittivity/permeability of the bulk and powdered material are assumed to be the same. Although the MG theory is derived for a purely dielectric material, an analogous approach is followed to obtain an expression for μ_r. The expression for the permeability is defined by equation (2.7) with each ε_r replaced with it's corresponding μ_r.

Of the three magnetic powders, only TT2-111 was useful for testing equation(2.7). Manganese zinc and strontium ferrite had to be excluded due to the lack of permeability data on sintered samples. In order to achieve the effect of studying the MG theory for several values of $|\mu_1/\mu_2|$, the permeability of the TT2-111 composites are calculated at 0.3193, 1.0373, 2.0245 and 4.0439 GHz. This is possible because of the drastic change in the microwave permeability for sintered TT2-111 shown in Figure 7. The permeability at 0.3193 GHz is 14.5-i(28.18) and decreases with frequency

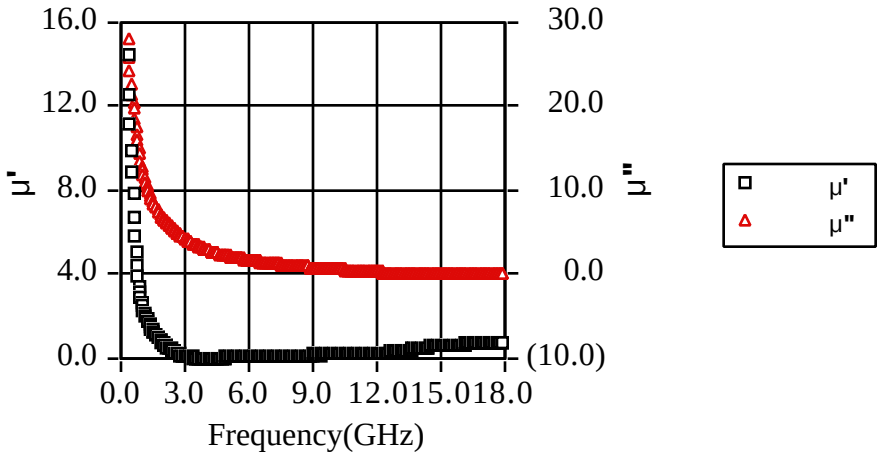


Figure 7. μ', μ'' as a function of frequency for sintered TT2-111.

until it reaches a minimum of 0.01-i(2.64) at 4.3580 GHz. At this point μ' increases to 0.72 at 17.9102 GHz. Above 13 GHz μ" becomes to small to measure using a coaxial airline/waveguide measurement technique. The phenomenon that occurs between 1.8001 and 17.9102 GHz is sometimes referred to as a microwave "ferromagnetic" resonance. The internal fields(anisotropy, exchange, etc.) in the ferrite couple together in such a way as to mimic the effect found in ferromagnetic resonance at lower frequencies. The difference being the microwave resonance is not sharply peaked but rather smeared out over a large frequency range. The μ" values decrease rapidly with frequency since the magnetic loss mechanisms are directly

proportional to the frequency of the applied field. Therefore, when these mechanisms can no longer keep up with the applied field, their effect becomes quenched and the material exhibits no magnetic properties.

Theoretical predictions from the MG theory and the TT2-111 permeability data are displayed in Figure 8. The MG theory is represented by a solid line and dashed lines represent second-order polynomials. Equation (2.8) is only plotted in Figure 8a for μ' and is depicted using a triangle. The 0.3193 GHz(8a) permeability ratio is $|\mu_1/\mu_2| \approx 0.033$. When the permittivity ratio decreased past 0.04, ε' data exceeded the results produced by equation (2.8). However, μ' data does not experience this type of behavior but rather falls on both sides of the theoretical curve. The ratio increases to 0.083 at 1.0373 GHz(8b) and is comparable to the permittivity ratio for D-38 loaded C-1504. This indicates μ' should exceed the results of the MG theory over the entire range of measured filling factor. Again, μ' does not exhibit the type of behavior established with permittivity data.

The ratio is increased even further to $|\mu_1/\mu_2| \approx 0.153$ at 2.0245 GHz(8c). According to TT2-111 permittivity data, theory should be able to model the permeability. However, theory exceeds experimental values. At 4.0439 GHz(8d) the permeability ratio is now 0.34 and the agreement with theory has worsened. The expected performance of the MG theory established with the permittivity data has not been achieved when applied to μ'. On the contrary, an increase in $|\mu_1/\mu_2|$ diminished agreement with theory indicating the MG theory is therefore not capable of modeling the permeability of composite materials.

The inability of the Maxwell Garnett theory to model the permeability of composite materials is attributed to a permeability difference in bulk and powder materials. A magnetic material is divided into sections called domains which are partly responsible for the material's permeability [51-53]. Each domain aligns itself in a preferred direction of magnetization in the presence of an external field. A net magnetization occurs in the direction of the applied field whose magnitude is determined by the domain structure of the material. During the sintering process, a powdered ferrite is exposed to extreme pressure and heat which is responsible for the formation of grains and domain boundaries. The grain size and domain structure depend heavily on the sintering process and help determine the permeability of the material [54,55]. Therefore, the resulting domain structure(hence permeability) in a sintered material is not the same as found in a single granular particle.

This difference in permeability is demonstrated at 2.0245 and 4.0439 GHz where the sintered ferrite has a μ' less than one. If the powdered material had the same domain pattern(permeability) as the sintered ferrite, experimental μ' data should immediately start to decrease with the addition of the powdered ferrite. On the contrary, Figures 8c and 8d show an increase in μ'. In order for the permeability to become less than one, a change in the permeability of the loading must transpire. This change occurs at high filling

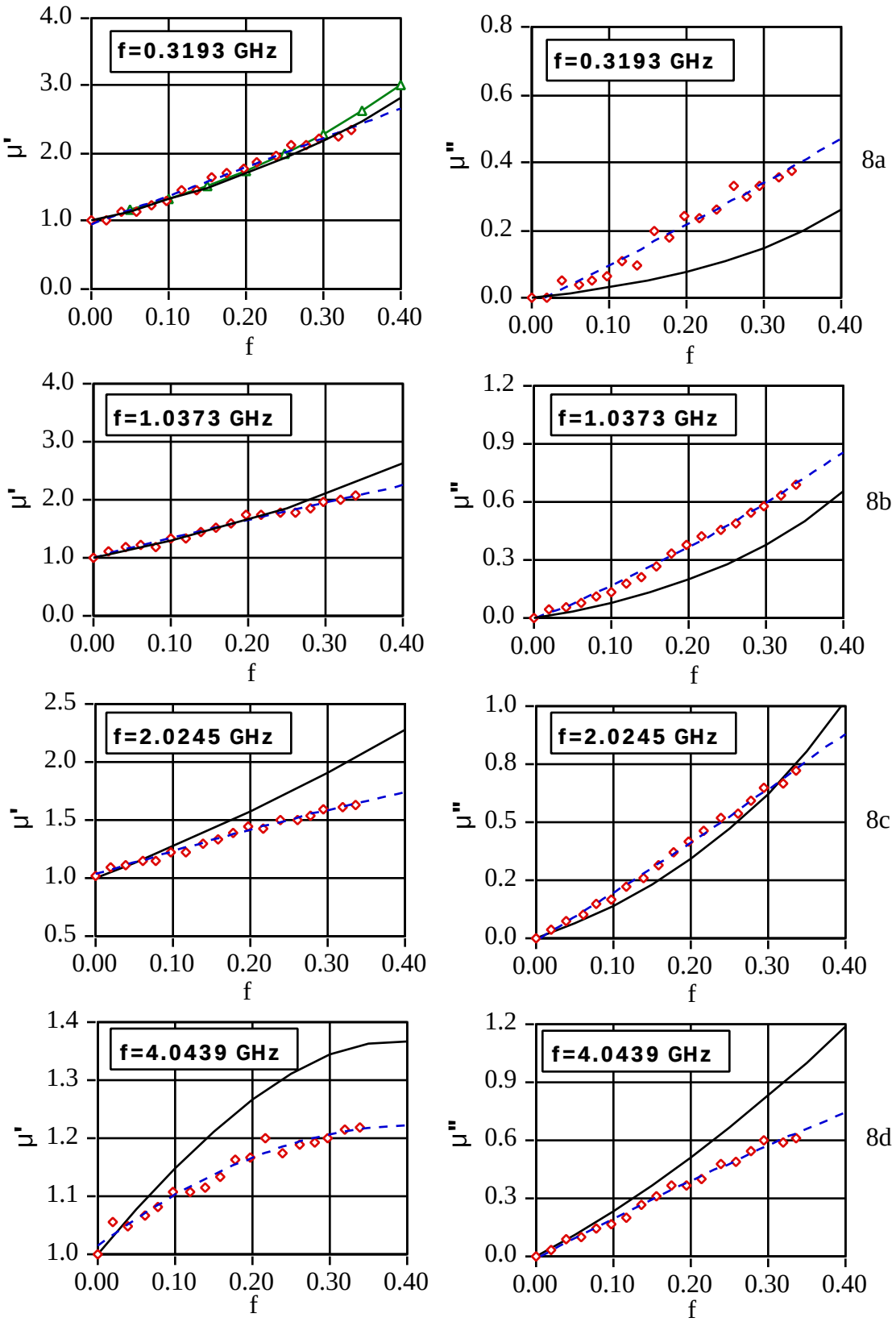


Figure 8. μ', μ" as a function of f for TT2-111 loaded C-1504.

factors where individual granules start to lose their identity and create larger grains with different domain structures.

Data for TT2-111 loaded C-1504 at 2.0245 GHz is extended to higher filling factors in Figure 9 with results taken from Ogasawara et. al. at 2.45 GHz [56]. They calculated permeability for nickel zinc ferrite loaded isoprene rubber(μ'=1) various filling factors up to 0.68. According to these results, μ' is still increasing at f=0.68. This indicates the individual powder grains are still retaining their independent domain configuration. The permeability will only become less than one when the domains in the composite become representative of the sintered material. The permeability difference in powdered and bulk material is also exemplified in Figure 10 where μ' is shown as a function of frequency for several different filling factors of TT2-111. It is observed that μ' increases with f but at some point decreases to the sintered value less than one. Figures 9 and 10 lend credibility to the argument that the MG theory can not possibly model the permeability of a composite material because it explicitly assumes the same permeability for a powdered and sintered ferrite.

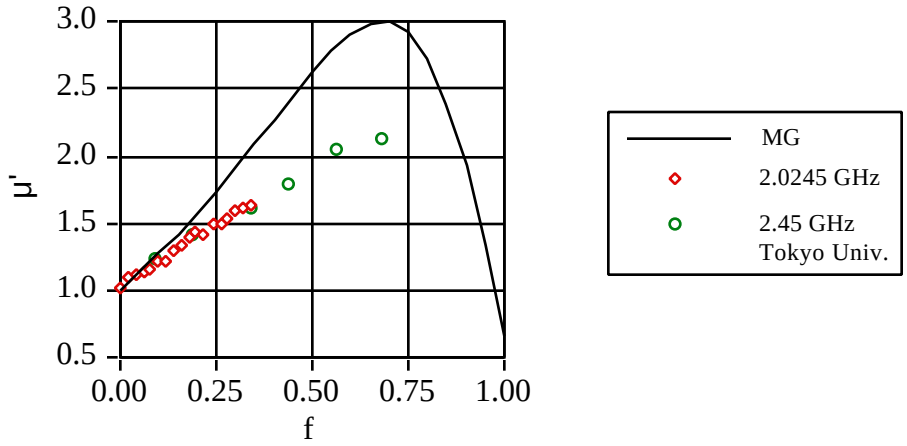


Figure 9. Comparison of TT2-111 and Tokyo University μ' data.

Although the manganese zinc ferrite composites could not be tested directly with the MG theory, results presented by Harrison et. al., indicates it is reasonable to expect μ'<1 for a sintered sample at microwave frequencies [98]. Based on this assumption, the 2.0245 GHz composite permeability data presented in Figure 11 again contributes credibility to the aforementioned arguments. Despite the failure of the MG theory, the permeability data presented for the TT2-111 and manganese zinc ferrite samples can be modeled using the second order polynomials(represented as solid lines in Figure 11) found in Figure 12.

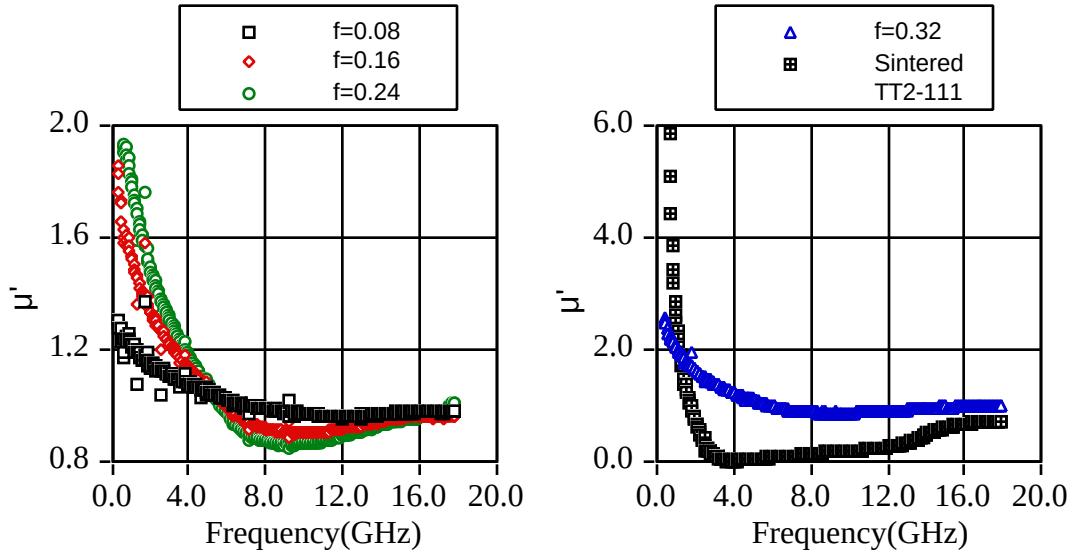


Figure 10. μ' as a function of frequency for TT2-111 loaded C-1504 at several values of f.

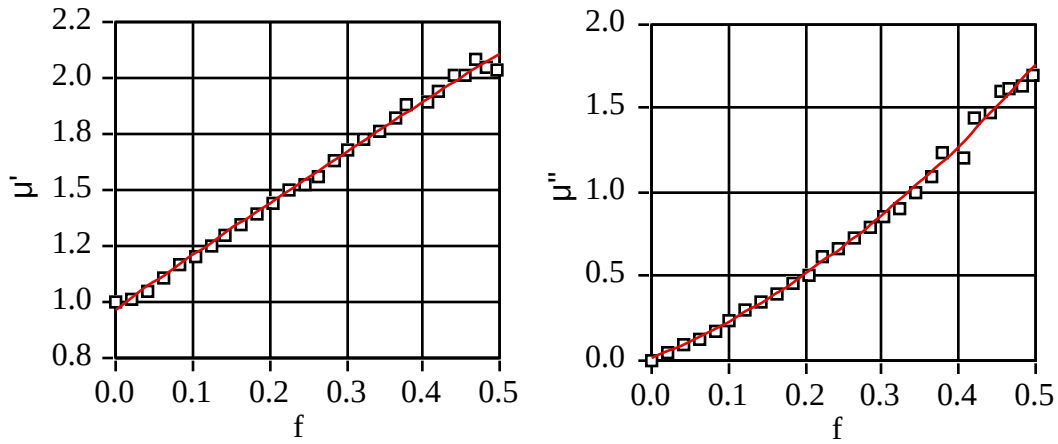


Figure 11. μ' as a function of f for manganese zinc ferrite loaded C-1504.

COMPOSITE(ε')	A	B	C	r^2
TT2-111(0.3193GHz)	-0.686	4.561	0.905	0.992
TT2-111(1.0373GHz)	-0.589	3.309	1.022	0.987
TT2-111(2.0245GHz)	-0.728	2.068	1.024	0.991
TT2-111(4.0439GHz)	-1.158	0.986	1.013	0.972
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	-0.196	2.382	0.966	0.996

COMPOSITE(ε")	A	B	C	r^2
TT2-111(0.3193GHz)	0.277	1.104	-0.018	0.971
TT2-111(1.0373GHz)	1.629	1.515	-0.003	0.995
TT2-111(2.0245GHz)	0.550	2.011	-0.012	0.997
TT2-111(4.0439GHz)	-0.358	2.023	-0.011	0.991
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	3.373	1.816	0.009	0.996

Figure 12. Second-order polynomials ($\varepsilon' , \varepsilon'' = Af^2 + Bf + C$) used to theoretically predict the permeability of the TT2-111 and manganese zinc ferrite composite materials.

CONCLUSION

The microwave permittivity and permeability of artificial dielectric and magnetic composite materials are tailored by introducing various loading agents to a host epoxy resin. The Maxwell Garnett theory's ability to model ε' is effective only for TT2-111 composites and is shown to gradually diminish with increasing ε_2. Second-order polynomials dependent only of f are utilized to theoretically predict ε' and ε" for the remaining composite materials. In addition, existence of a limiting form of the MG theory is uncovered and experimentally established when the condition $|\varepsilon_1/\varepsilon_2| \leq 0.04$ is satisfied.

The expected performance of the MG theory established with permittivity data was not achieved when applied to permeability data. It's failure is attributed to a permeability difference in bulk and powdered material arising from contrasting domain structures. Results from literature extended TT2-111 data indicating a change in loading agent permeability must occur at high filling factors. The transition occurs when individual granules lose their identity and help create larger grains with different domain structures. Despite the failure of the MG theory, permeability of artificial composite materials is effectively tailored using second order polynomials.