Electromagnetic Absorption of a Nickel Zinc Ferrite System at Low Frequency

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Abstract

In this report we investigate the electromagnetic absorption qualities of a material-metal system in the frequency range of 1 MHz to 1.5 GHz. The system is composed of a perfectly reflecting metal surface which is coated with a thin layer of Nickel Zinc Ferrite ($Ni_{0.65}Zn_{0.35}Fe_2O_4$). We find that this system is a relatively good electromagnetic absorber for large coating thicknesses and has average reflected energy values that dip below twenty percent.

1 Introduction

Whenever an electromagnetic wave is incident on a single material or mixture of materials some of the wave will be reflected and some will be transmitted or dissipated as heat depending on various characteristics of the material system. For some applications it would be useful to reduce the radiation that is reflected from the surface of the system and have as much as possible be transmitted through or damped out. An electromagnetic absorber is a material or mixture of many materials that does exactly that: it minimizes the reflected wave energy.

There are many diverse applications for such an absorbing system. The most obvious is radar absorption where the material system is tuned so that very little energy is reflected from the surface for frequencies in the radar band. This allows the object that is coated with the material system to be invisible to radar and undetectable. This type of setup has obvious applications in military settings to produce stealth technology. Other applications include photovoltaic cells, which have an absorbing material which transmits as much power as possible to the diodes, and anechoic chambers, which are rooms where the walls are covered with electromagnetic absorbers so that any electromagnetic measurements conducted in the rooms are minimally influenced by reflected energy from inside the room.[1]

The simplest type of absorber is a material or system of materials whose effective impedance Z (which is defined here as the impedance of the material or system of materials divided by the impedance of free space) is equal to or very nearly equal to the impedance of free space (one) for all frequencies. This can be seen by the simple reflectance equation

$$R = \mathrm{Mod}\frac{\mathrm{Z}-1}{\mathrm{Z}+1} \tag{1}$$

where Z is generally complex and R is the reflectance, or the reflected wave amplitude divided by the incoming wave amplitude. When $Z \approx 1$ for all frequencies, the reflectance is very small and therefore the reflected energy (which is simply the reflectance squared) is even smaller. If a material system of this type were placed in front of an electromagnetic wave, the wave would simply pass through and very little reflected energy would be detected.

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[1] Perambur S. Neelakanta, *Handbook of Electromagnetic Materials*, CRC Press, New York, 1995

For most cases though, the analysis is not quite as simple. Most generally, the impedance is complex and depends on the frequency of the incoming electromagnetic wave. In this more general case, the reflectance will still be a real number (it has to be– you can measure it), but it will depend on frequency so that the quality of the absorber will depend on the incident frequency of electromagnetic wave. Also, instead of the incoming wave simply transferring its energy to a transmitted and reflected wave, some of the energy will be converted to heat because of the imaginary part of the impedance.

Additionally, single material electromagnetic absorbers are rarely used because it is rare that the impedance characteristics are sufficient to produce minimal reflection. Because of this, more elaborate geometries are used and the effective impedance of these geometries must be found. Electromagnetic absorbers where more than one material are used are generally called composite absorbers.

2 One Particular Composite Absorber

The particular geometry that we used for our investigation is shown in Fig 1. It consists of a perfectly reflecting metal that is coated by a thin layer of material (on the order of millimeters). Since we are looking for absorbing systems that work in the wavelength range of tenths of meters to hundreds of meters, this material coating is quite small compared to the incident wavelength. Therefore, it is necessary to treat the absorber as a system (since the electromagnetic wave can "see" past the coating) and we must find the effective impedance of the system instead of the impedance of the coating alone.

The derivation of the effective impedance of such a geometry has been treated in many texts and is not pursued for reasons of brevity.[2] The general procedure of the derivation is to relate the incoming electric and magnetic fields to the electric and magnetic fields in the metal by use of a two by two matrix. This matrix can then be used to find an effective impedance of the system. Using a derivation in this spirit, it can be determined that the effective impedance of a material-metal system is

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[2] Ruck, *Radar Cross Section Handbook, Vol. 2*, Plenum Press, New York, 1970

$$Z = -i\sqrt{\frac{\mu}{\epsilon}}\tan\left(\frac{2\pi t}{\lambda}\sqrt{\mu\epsilon}\right) \tag{2}$$

where $i = \sqrt{-1}$, μ is the relative permeability of the material (the permeability of the material divided by the permeability of free space), ϵ is the relative permittivity, t is the thickness of the coating, and λ is the wavelength of the incoming electromagnetic wave. Now that we have the effective impedance of the material-metal system, we can insert it into (1) and have an equation that gives the value of the reflectance. This equation is quite complicated, containing six independent variables: real and imaginary permeability, real and imaginary permittivity, wavelength, and thickness.

The zero reflectance case (or the case when $Z = 1$) has been studied extensively.[3] In these papers, the authors set certain combinations of the six variables equal to constants and find values for the rest of the variables for which the reflectance is zero. Then they plot these values and make a so-called impedance matching solution map which gives many possible combinations of the six variables for which there will be no reflected wave. An example of one of these maps is shown in Fig 2. Although these graphs are quite easy to read and very helpful for certain cases, their use is limited. For example, it is not possible to find the actual value of the reflectance if it is not exactly zero, and for many applications the reflectance does not have to be totally eliminated but just significantly reduced. So if the reflectance is not zero, these maps will not be able to tell you whether it is 0.0001 or 1.

Instead of using the impedance matching solution maps for our analysis, we simplified the actual reflectance equation by experimentally finding values for the permittivity and permeability of our material. This reduces the reflectance equation to a simpler function of only two variables, namely frequency and thickness of coating. We can then examine this function to find the value of thickness that will most reduce the reflected energy over the frequency range we tested. Although this method loses generality in that the results are only valid for our particular geometry and materials, it gives us more information and can be easily applied to other situations. An overview of the methods we used to analyze our data, including Mathematica code to carry the analysis out, can be found in Appendix A.

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[3] H. M. Musal, Jr. and H. T. Hahn, "Thin-Layer Electromagnetic Absorber Design", *IEEE Transactions on Magnetics, Vol. 25 No. 5*, Sept. 1989, pp. 3851-3854

3 Experiment

The instrument that was used to find the experimental values was the HP 4291B. This instrument will accurately take permittivity and permeability measurements at frequencies from 1 MHz to 1.5 GHz. To find the permittivity of a material, the instrument requires that a pellet of the material to be tested is placed in a circuit and acts as a capacitor. The machine finds the impedance of the material using $Z = V/I$ (for different set frequencies of the voltage) and from this impedance can calculate the relative permittivity of the material as a function of frequency. Similarly, for measurements of permeability, the machine requires a solenoidal pellet that can act as an inductor, and the relative permeability can once again be determined from the impedance.

For the actual experiment, we used a Nickel Zinc Ferrite pellet ($Ni_{0.65}Zn_{0.35}Fe_2O_4$) that was originally in powder form and pressed at room temperature at a pressure of five metric tons per square centimeter. For both the permeability and permittivity measurements, the diameter of the pellet was less than three centimeters. Using these pellets (one for each measurement μ and ϵ) along with the HP 4291B we experimentally determined μ and ϵ as functions of frequency. The experimental graphs of these values are shown in Figs 3 and 4.

We would expect, to a first order approximation, that the material-metal system would have the best absorption qualities when both the imaginary permittivity and imaginary permeability of the ferrite material take on their maximum values. Since these two parameters both take on relatively high values for frequencies above 120 MHz, we should see (as we will in the next section) that the reflectance is quite low for this region since so much of the incoming wave is damped out.

4 Results

Placing the experimental values for the permeability and permittivity as functions of frequency into (2), we can calculate the effective impedance of the material-metal system, and from that impedance find the reflectance. Fig 5 shows the reflectance plotted as a function of thickness and frequency for our ferrite covered metal. The top plot covers all frequencies tested while the bottom plot only covers the frequencies for which the reflectance rapidly changes. The thickness of ferrite material varies from zero to 10 mm for both plots. Since the top plot covers all frequencies tested, the values of reflectance in the high-frequency, high-thickness region are not very exact at all. For this region it is better to refer to the bottom graph.

As was expected simply from the imaginary permittivity and permeability plots, the reflectance begins to visibly drop around 120 MHz. It then proceeds to dramatically plummet at about 950 MHz. Although the three dimensional plots in fig 5 give a good sense of the value of reflectance at any thickness-frequency point, our main goal is to find a thickness for which the reflectance is minimized over all frequencies tested. In other words, we want to find one thickness of material that will work the best to absorb all tested frequencies.

In order to do this, we developed a method to find the average value of the reflectance (averaged over all tested frequencies) as a function of thickness. This plot is shown at the top of fig 6. Also in fig 6 is a plot of the average reflected *energy* which is simply reflectance squared. Both plots drop quickly for small values of coating thickness and then level out somewhat as coating thickness increases. There is no minimum value in the graphs, therefore we must find the *best* value. In order to find the most beneficial coating thickness we must take into consideration manufacture, cost, practicality, and other issues. Ultimately, the decision depends on the application in which the absorber will be used. For example, to coat the walls of a anechoic chamber the coating thickness can be large, whereas to coat the outside of a plane the coating thickness can not be very large at all. Because of the different applications, we will not quote a best value, but rather leave the plots in fig 6 as a guide to help find the best thickness value for any particular application.

5 Conclusion

An electromagnetic absorber system consisting of a perfectly reflecting metal coated with a Nickel Zinc Ferrite has been examined in the frequency range of 1 MHz to 1.5 GHz and found to have relatively good absorbing qualities at sufficiently high coating thicknesses. The absorbing system is not extremely good since the average reflected energy stays above ten percent for all reasonable thickness values, but for certain applications, just an absorber might be needed.

6 Acknowledgments

We would like to thank the NSF and The Ohio State University for the funding of the 1999 REU program. Additionally, thanks to Dr. William Palmer and Dr. Linn Van Woerkem for heading the program and giving direction when needed. Finally, I would like to thank Dr. Epstein and Dr. Nandyala for giving me the opportunity to do this particular work.

7 Appendix A

In this appendix we describe the methods of analysis that were used to procure the results quoted in the report. We used Mathematica to analyze the reflectance equation, and some types of analysis that we did not use in the report are also mentioned in this appendix. All of the methods in some way relate the reflectance to either the frequency of incoming electromagnetic radiation or the coating thickness. Keep in mind that to find the fraction of *energy* reflected, the reflectance is simply squared.

For all of the types of analysis listed below, the first thing to do is input the data. It is assumed that the data has been inputted and the symbols used are f for the frequency, ϵ' for the real permittivity, ϵ'' for the imaginary permittivity, μ' for the real permeability, and μ'' for the imaginary permeability. These will all be simple lists and μ'`[[n]]` will correspond to the nth number in the list that is μ'. Additionally, it is assumed that the user has inputted the impedance equation ($Z = \ldots$) and the reflectance equation ($R = \mathrm{Abs}\frac{\mathrm{Z-1}}{\mathrm{Z+1}}$).

7.1 Plotting Reflectance vs Coating Thickness

Doing this is simple enough, you only have to enter one line:

```
Plot[R[[f]], {t, minvalue, maxvalue}]
```

where f is an integer which corresponds to the list number (of data) that the frequency value is at.

7.2 Plotting Reflectance vs Frequency

If many frequencies must be absorbed, this method will show how the reflectance varies with all of the frequencies (for a set thickness).

```
t = valueofcoatingthicknesstocheck;
ListPlot[Table[{f[[n]], R[[n]]}, {n, 1, maxlistnumber}]]
```

In this command, max list number is simply the number of data points that you have.

7.3 3-D Plots of Reflectance vs Frequency and Thickness

The applicability of this plot is in gaining a general idea of how the reflectance changes with both parameters. The plots that are produced will not give a quantitative measure, but will give a good idea of the frequencies and thicknesses for which the reflectance is qualitatively low. Then you could use the two dimensional plots to quantify the reflectance.

```
pts = Table[R[[n]], {t, minvalue, maxvalue, stepsize}, {n, minflistnumber, maxflistnumber}];

                                 ListPlot3D[pts]
```

7.4 Plots of Average Reflectance vs Thickness

This plot give a good idea of how the average reflectance changes with thickness. It helps when choosing a best thickness for the coating.

```
pts = Table[{t, (Sum[(f[[i + 1]] − f[[i]])R[[i]])/(f[[maxlistvalue]] − f[[1]]},
      {i, 1, maxlistvalue}], {t, minvalue, maxvalue, stepsize}];
              ListPlot[pts, PlotJoined− > True]
```

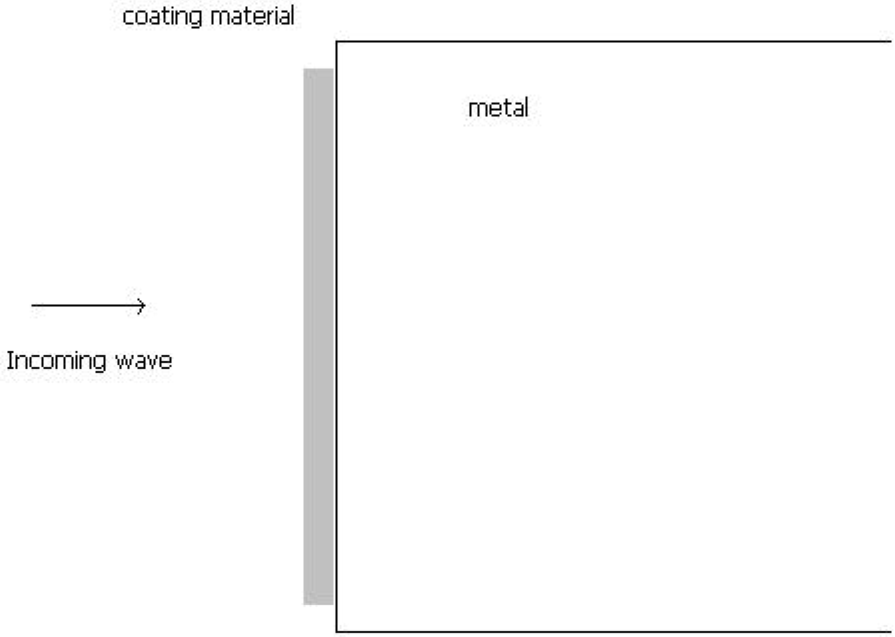
7.5 Animated Plots

Just for fun (and it is somewhat informative) you can also animate a plot of reflectance vs frequency for changing thickness values. By doing this, you can see how the reflectance vs frequency plot changes as the thickness increases without having to look at a three dimensional graph.

```
    Animate[ListPlot[Table[{f[[n]], R[[n]]}, {n, 1, maxlistvalue}],

PlotRange− > {{f[[1]], f[[maxlistvalue]]}, {0, 1}}, PlotJoined− > True],

              {t, minvalue, maxvalue, stepsize}]
```



In our geometry, there is a large, perfectly reflecting piece of metal which is thinly coated by the Nickel Zinc Ferrite. The thickness of the coating is small compared to the wavelength of incoming radiation.

Figure 1
Diagram of the geometry

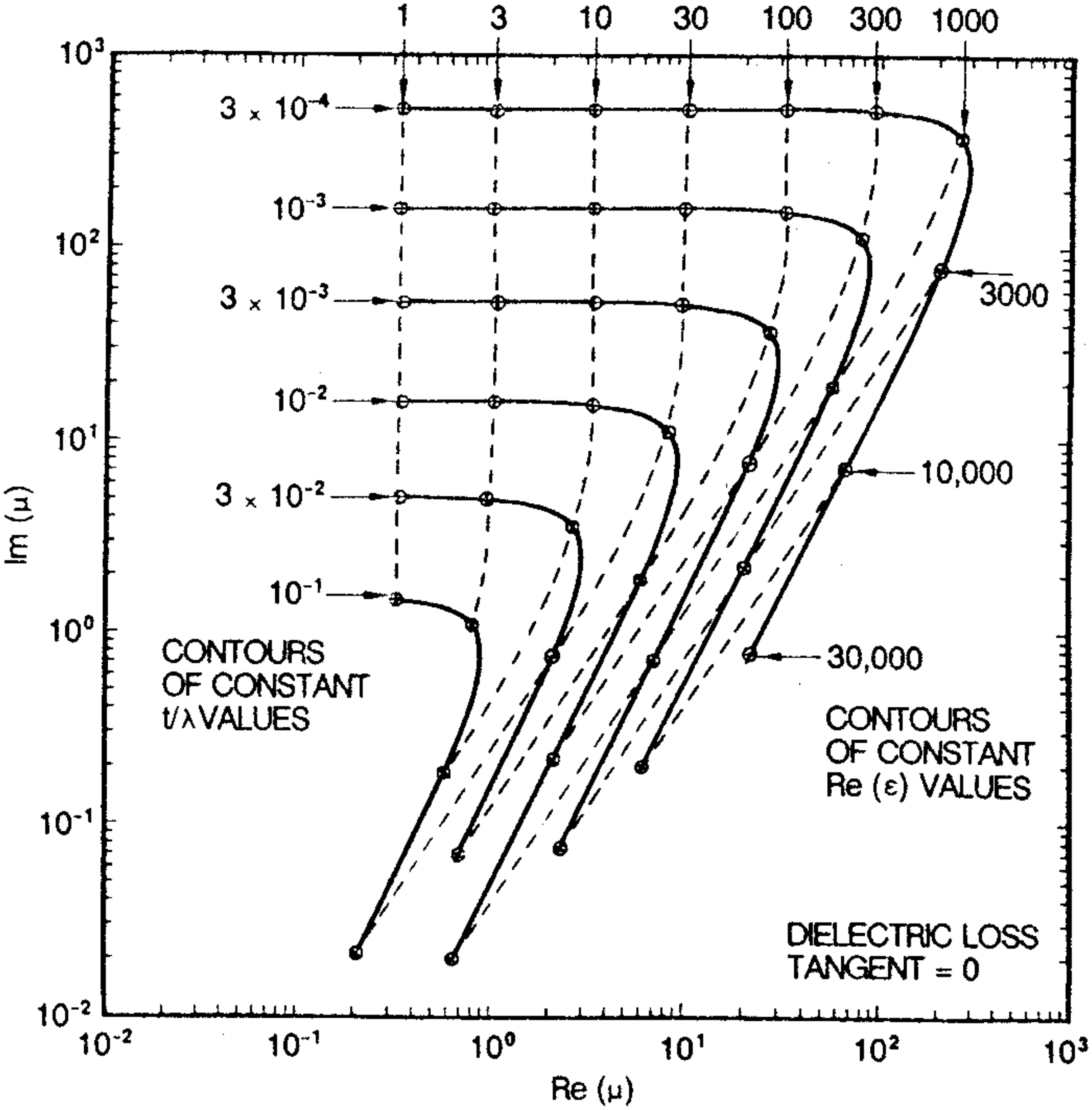
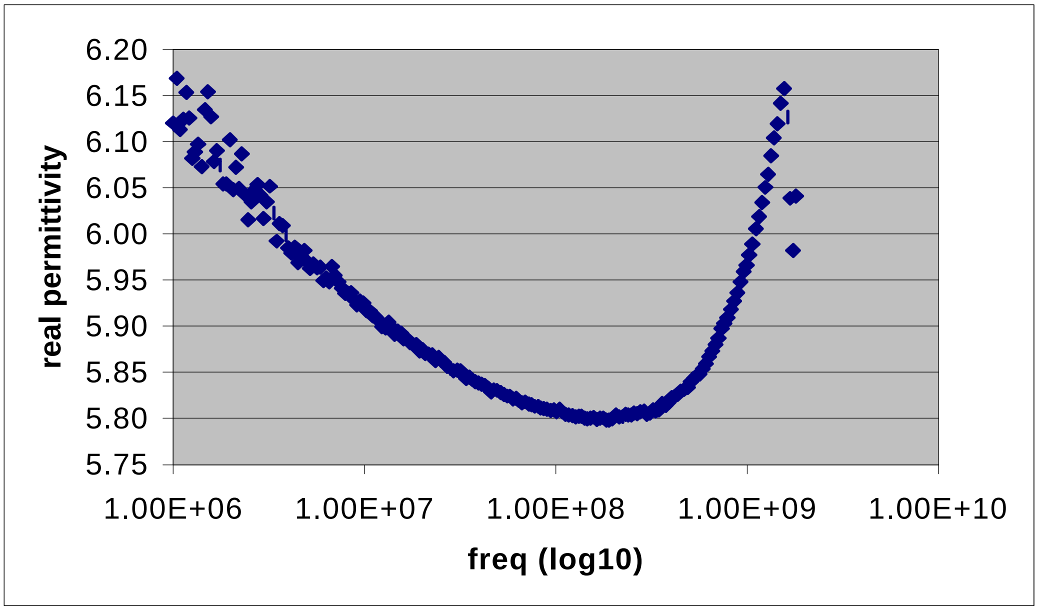


Figure 2
Impedance matching map taken from *IEEE Transactions on Magnetics.* For more information on the paper, check reference [3] on page 4 of the report.



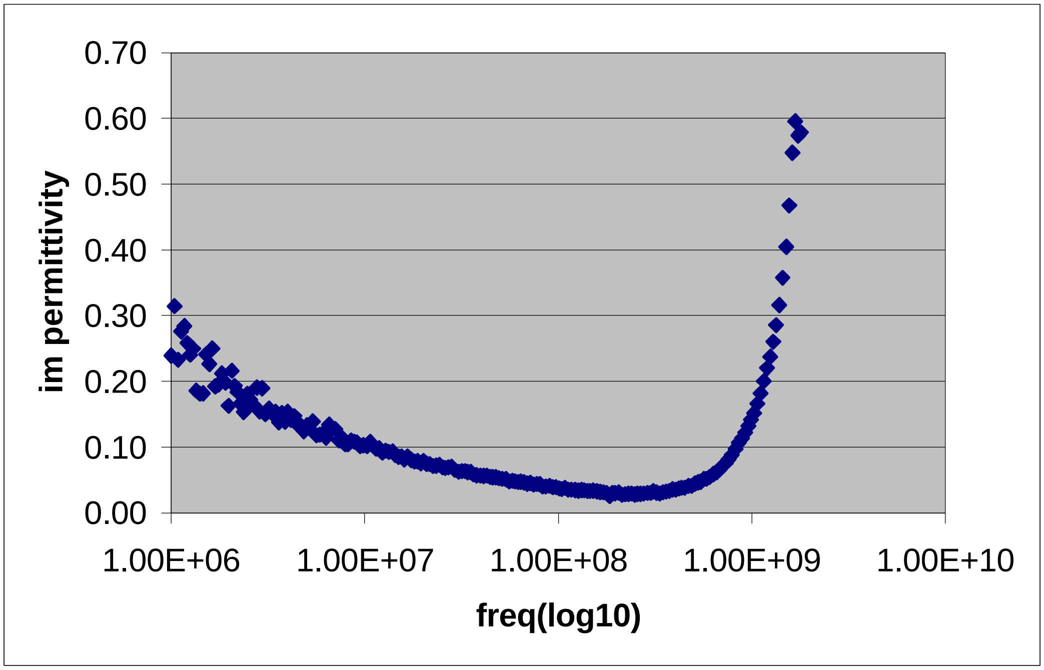
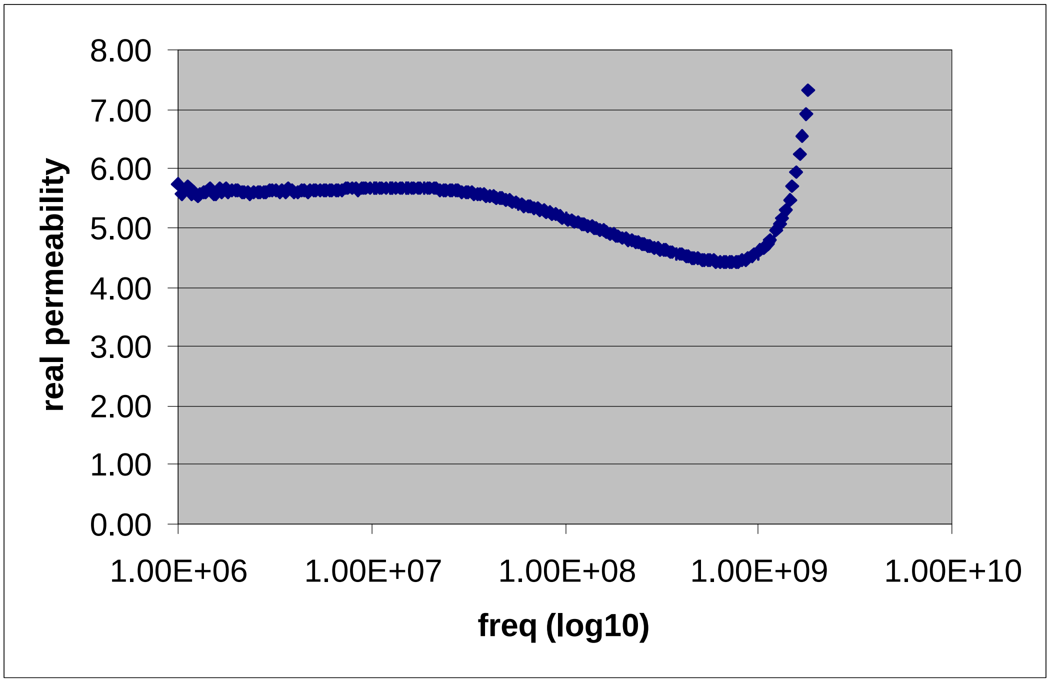


Figure 3
Plots of real and imaginary permittivity for the sample



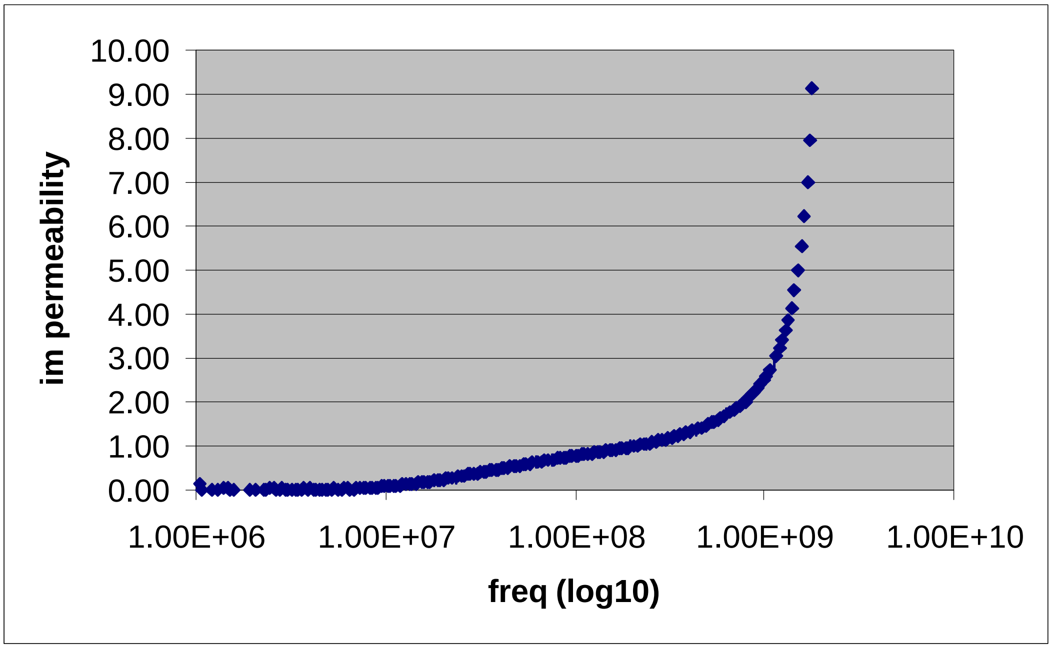


Figure 4
Plots of real and imaginary permeability for the sample.

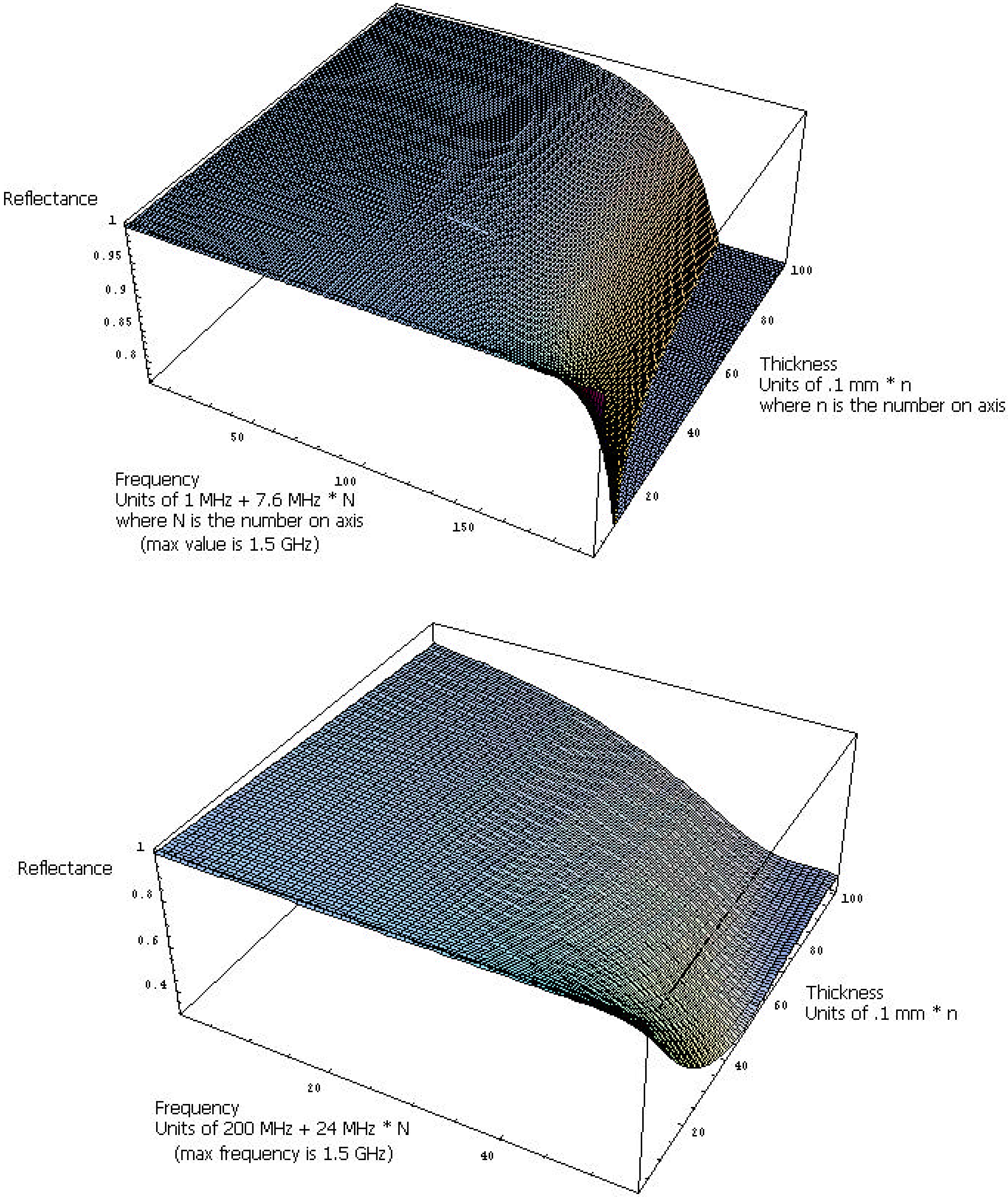


Figure 5
Plots of reflectance vs frequency and thickness for two different frequency ranges.
The top graph is for all frequencies tested (1 MHz to 1.5 GHz), and the bottom graph
goes into the range where the reflectance decreases more rapidly (200 MHz to 1.5 GHz).
Thickness varies from zero to 10 mm in both plots.

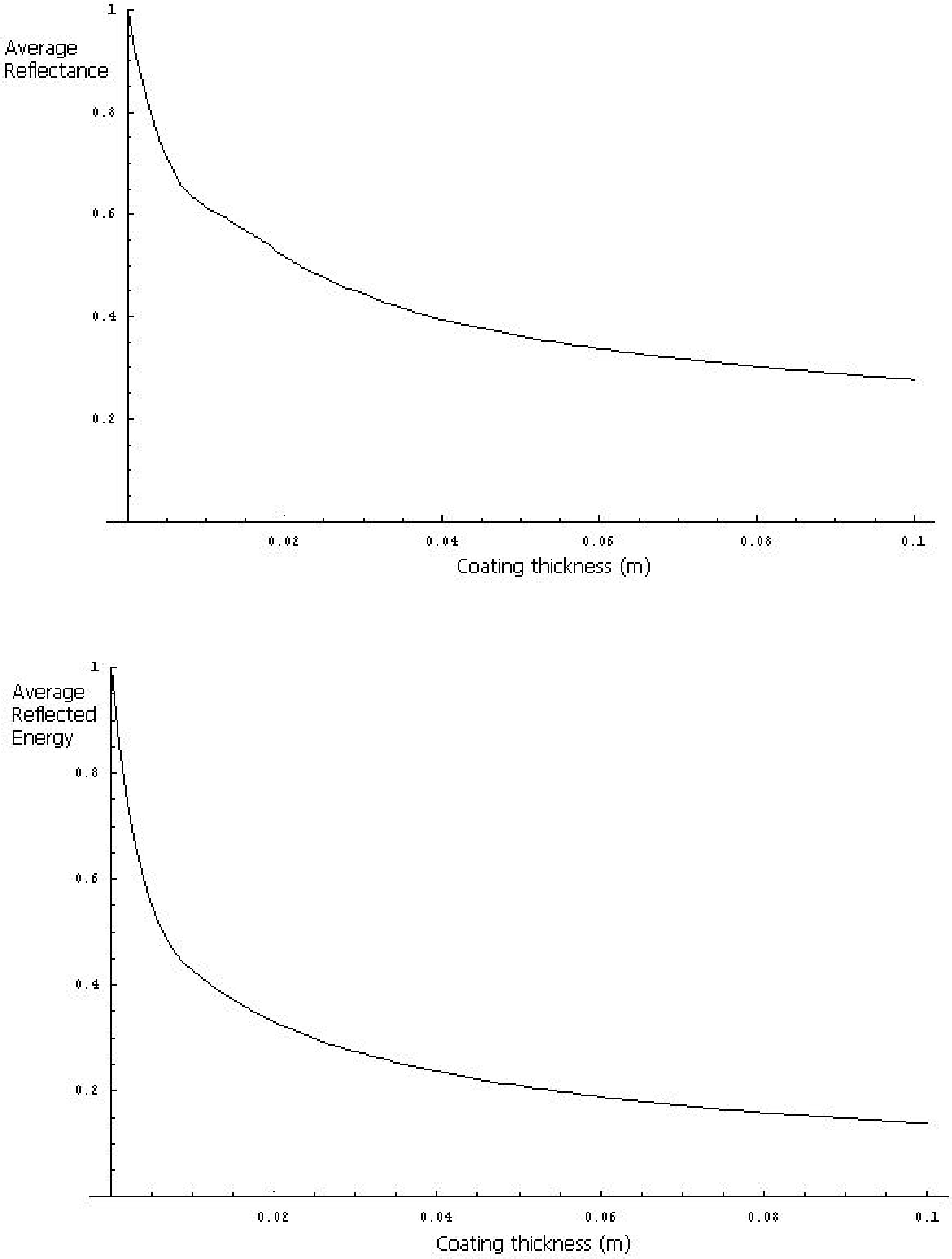


Figure 6
Average Reflectance and Energy Reflected averaged over all frequency values tested (1 MHz to 1.5 GHz) plotted against coating thickness. Energy Reflected equals one corresponds to all of the incoming radiation being reflected.