THE DEVELOPMENT AND CHARACTERIZATION OF HYBRID THERMAL/EMI SOLUTIONS FOR ELECTRONICS

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ABSTRACT
Products that manage thermal and electromagnetic challenges individually in electronics are well established in the current marketplace, but a need has emerged for materials and solutions that combine these two functionalities. In many new products and designs multiple heat and signal generating components cannot be isolated from each other using traditional means. In these applications a material that transfers heat and absorbs electromagnetic energy can be used to improve signal integrity, prevent crosstalk, and manage operating temperatures. These hybrid materials have various compositions and forms, which range from thin sheets to soft pads to reactive or non-reactive liquid materials. The mechanical, thermal, electrical, and magnetic properties of these materials depend on their materials of construction as well as the macro and microscopic organization of the components involved. Many test methods exist to measure the thermal and electromagnetic properties of a material both in an application and as fundamental material properties. This paper will expand on these topics in more detail as well as discussing existing and future trends in thermal and electromagnetic materials development.

Key words: Thermal management, EMI, absorption

INTRODUCTION
Heat generation and unwanted electromagnetic interference are issues that have become more and more critical in modern electronic devices as the overall size of the devices decreases and the component density increases. For example, the thicknesses of two common mobile phone types has decreased significantly in the last 10 years as can be seen below in Table 1 [1].

Table 1. Mobile phone thickness variation with generation

	Thickness (mm)		**Thickness (mm)**
Phone1 Gen1	11.7	Phone2 Gen1	9.9
Phone1 Gen2	12.2	Phone2 Gen2	8.5
Phone1 Gen3	9.4	Phone2 Gen3	8.6
Phone1 Gen4	7.6	Phone2 Gen4	7.9
Phone1 Gen5	6.9	Phone2 Gen5	8.1

As devices get smaller and smaller the space required to shield each component individually with an EMI can begins to present a conflict with the overall assembly size. In these cases multiple signal generating components often have to be grouped under one can. Additionally, the space for thermal solutions needs to be reduced as well, all of which necessitate solutions that combine thermal and EMI solutions. Since the elimination of crosstalk and other EMI issues inside of a shielded enclosure can be difficult using traditional electrically conductive shielding materials, materials that absorb electromagnetic energy as opposed to reflecting it are of particular utility.

It should also be noted that while the example above of the shrinking thickness of mobile phones provides an idea of how electronics are changing, applications for thermal and EMI solutions exist in many other industries as well. Electronics have become and will continue to be prevalent in automotive applications as autonomous driving and infotainment technologies proliferate [2]. Power conversion and switching as well as telecom applications are also common areas where thermal management and EMI solutions are needed and are being squeezed by higher speeds and smaller form factors.

BACKGROUND

EMI and Thermal Material Composition

The materials that are used to manage heat generation and thermal transfer in electronics are often quite similar to those that are used for EMI management. Typically a polymeric matrix is combined with one or more fillers to form a composite structure that conducts and/or absorbs heat. This same construction is used for EMI management with fillers that conduct away and/or absorb unwanted signals.

The polymeric matrix mainly functions to keep the fillers in place and to provide the necessary mechanical, thermal, and chemical properties of the composite. In some cases, for example an adhesive, a more rigid or tough matrix may be desirable. In other cases, like a Gap Pad® or gap filler, a soft, compliant material would be ideal to prevent residual stresses on components and to take up vibration and thermal expansion. Similarly, some applications may require a material with a high heat resistance, while others may not.

In the case of thermal management materials the thermal conductivity is generally provided by metal oxides to give a balance between costs, performance, and to minimize electrical conductivity. In more specialized cases, other ceramics such as boron nitride, aluminum nitride, and silicon carbide or metals are used. Thermal absorption typically comes from materials that undergo a phase transition at the temperature of interest. Waxes and low melting metal alloys often fall into this category [3, 4].

For EMI management, the trend is similar, but different fillers are typically used. For shielding/electromagnetic reflection a composite with bulk electrical conductivity is usually needed. This set of properties is achieved by using electrically conductive fillers above their percolation threshold. Electromagnetic absorption through the use of soft magnetic materials with a high loss tangent at the frequency of interest is a common technical solution [5].

The form factor or method of delivery and use of thermal and EMI management materials is widely varied. These solutions come in the form of thick, compliant pads, thin tapes and sheets, reactive materials that cure to form soft interfaces, structural adhesives, and uncured pastes.

Electromagnetic Background

Materials that are used for electromagnetic shielding or absorption function as shown below in Figure 1 [6].

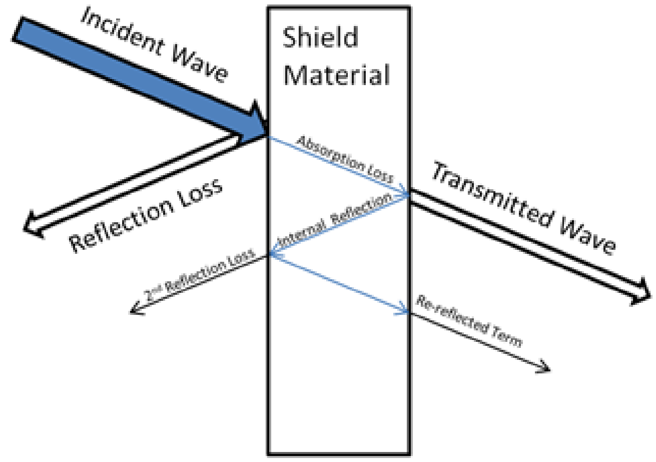

Figure 1. Electromagnetic Shield Performance

The incoming signal is partially reflected from the shield surface, some of the signal is absorbed, a portion of the signal is reflected from the opposite side, and the remaining signal continues on. The ratio of the incident (E_i) to transmitted energy (E_t) can be used to define the shielding effectiveness (SE) as shown below. It should be noted that the shielding effectiveness lumps absorption and reflection together to give the total amount of shielding [6].

$$SE\ (dB) = 20\log(E_i/E_t) \quad (1)$$

The absorption capability (A) of a material can be defined as shown below [6]. It should be noted that the absorption is a function of the signal properties as well as the magnetic permeability and dielectric permittivity of the material itself.

$$A = \tfrac{1}{2}\sigma E^2 + \tfrac{1}{2}\,\omega\varepsilon_0^2\varepsilon_R E^2 + \tfrac{1}{2}\,\omega\mu_0^2\mu_R H^2 \quad (2)$$

A (W/m^3) = EM energy absorbed per unit volume
E (V/m) = Electric field strength of incident radiation
H (A/m) = Magnetic field strength of incident radiation
σ (S/m) = Electrical conductivity of the material (R = relative to copper)
ω (1/s) = Angular speed of the EM wave = $2\pi f$ (f = frequency)
ε (F/m) = Dielectric permittivity (0 = vacuum, R = relative)
μ (A/m) = Magnetic permeability (0 = vacuum, R = relative)

The absorption loss in a material is described by the following equation [5]. In general, an increase in thickness, permeability, and permittivity will contribute to more absorption.

$$\text{Absorption loss} \propto t(\mu f\sigma)^{1/2} \quad (3)$$

t = Thickness
Skin depth = $1/(\pi\mu_R\,\mu_0\,f\sigma)^{1/2}$

The power of a wave decays in a material with distance (x) by the factor $e^{-\alpha x}$ [7].

$$\alpha = (\mu_0/\varepsilon_0)^{½}\omega(a^2+b^2)^{1/4}\sin[(½)\tan^{-1}(-a/b)] \quad (4)$$
$a = \varepsilon_r\mu_r-\varepsilon_i\mu_i$; $b = \varepsilon_r\mu_i-\varepsilon_i\mu_r$ (r = real, i = imaginary)

And lastly, the reflection from a material is defined as [8].

$$R = [(\mu_R/\varepsilon_R)^{½}-1]/[(\mu_R/\varepsilon_R)^{½}+1] \quad (5)$$
R= Reflection coefficient

By taking all of these equations together we can start to understand the complexity of the situation when an incident electromagnetic wave contacts a material. In some cases, reflection is desired without absorption, in others absorption is needed without reflection, and in other situations the overall shielding effectiveness is the main property of concern. Large values of permeability and permittivity are often related to improved performance, but they can counteract each other in some cases, such as when absorption is desired but not reflection.

Thermal Background

A thermal interface material (TIM) serves to transfer heat from one location to another in an electronic assembly so the necessary components do not overheat. This effect is achieved by reducing the thermal resistance between two or more substrates. Microscopic irregularities on a given substrate trap air at the interface, which then acts to insulate the materials from each other. The thermal interface material displaces the air and provides a thermal path for heat transfer. Improving the thermal conductivity of the interface material is one way to reduce the thermal resistance, but decreasing the bondline between the two substrates is also critical for improving heat transfer. The relationship between thermal conductivity and the bondline and thermal resistance is shown below [3].

$$k = \frac{dq}{dt}\cdot\frac{z}{A\Delta T},\ R_\theta = \frac{z}{kA} + R_i,\ Z_\theta = \frac{z}{k} \quad (6)$$
k = thermal conductivity, q = heat flow, t = time, z = thickness, A = area, T = temperature, R_θ = overall thermal resistance, R_i = interfacial thermal resistance, Z_θ = overall thermal impedance

As is further illustrated in Figure 2, at a given level of thermal conductivity, the thermal impedance can be significantly reduced by shrinking the bondline.

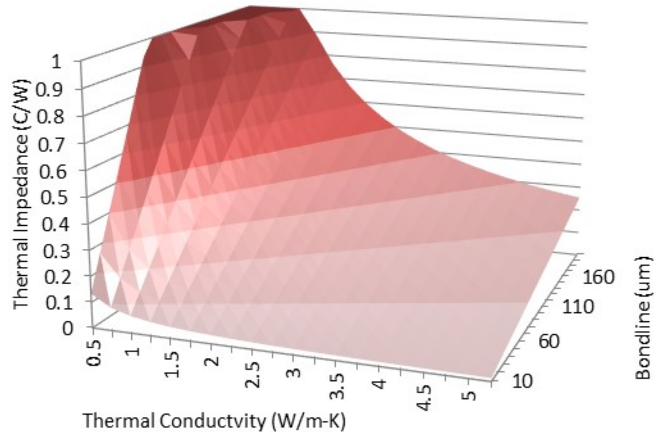

Figure 2. Variation in Calculated Thermal Impedance with Thermal Conductivity and Bondline

In addition to the thermal conductivity and bondline, additional factors such as reliability, mechanical properties, thermal and chemical stability, and electrical conductivity and dielectric constant also come into play when selecting a thermal interface material.

Hybrid Materials

The remainder of this paper will discuss the development and characterization of materials that combine thermal and EMI management. Specifically, it will focus on materials that conduct heat and absorb electromagnetic radiation. As has been discussed for EMI and thermal management, this result is achieved though the proper combination of fillers and a matrix to yield a composite with the desired properties. A particular challenge with most hybrid materials targeting absorption involves avoiding reflection and electrical conductivity while absorbing as much signal and conducting as much heat as possible.

TEST PROCEDURES

Electromagnetic Testing

The permeability and permittivity of the materials tested was determined using ASTM D5568. A vector network analyzer was connected to waveguides to measure the S-parameters of the specimens under evaluations and a Nicolson-Ross model was used to calculate the relevant material properties [9]. The specific test setup used for 1.6-2.6GHz is shown below in Figure 3.

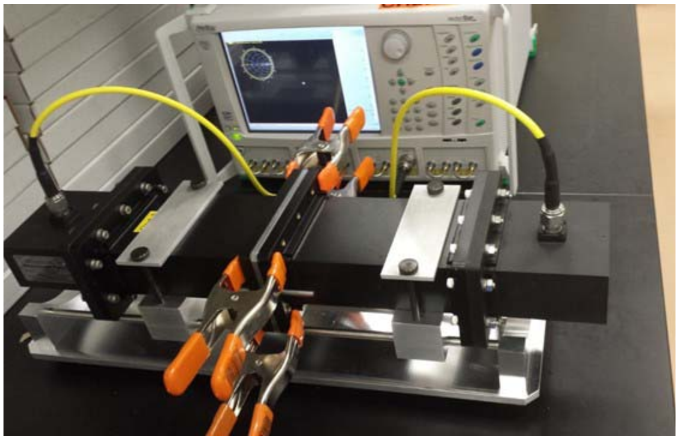

Figure 3. ASTM D5568 Test Setup

This particular test method was chosen for the ease with which it can be used for sheets of material as well as the sample dimensions in the 1-10GHz frequency range of interest. This frequency range was chosen because of the prevalence of the 2.4 and 5.0GHz Wi-Fi frequencies. Other test methods are available, including microstrip, coaxial, free space, and resonant cavity methods [6].

For measurements outside of the 1-10GHz range, an external lab was used for testing. Measurements below 1 GHz were performed using a coaxial fixture attached to a vector network analyzer in compliance with ASTM D5568 [9]. Measurements above 10GHz were conducted using a free space test fixture.

Additional testing was performed to determine the performance of hybrid EMI absorbing/thermal pads in representative applications. The first test vehicle is outlined in Figure 4. It consisted of an off the shelf chip loop antenna that radiated at 1.5 GHz and a test array of near field probes.

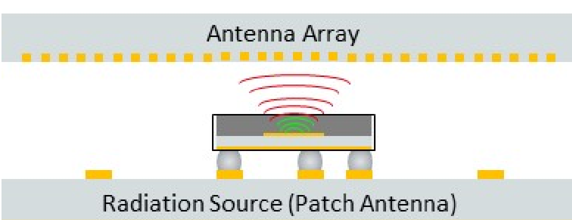

Figure 4. Patch Antenna Test Vehicle

In order to evaluate material performance an absorbing sheet of material was placed on the patch antenna and the difference in measured signal with and without the absorber was measured.

A second test vehicle was used to determine material performance in power supply application using a 1kW AC to DC converter. This setup is more representative of lower (~300MHz) frequency applications. Figure 5 shows the test setup, with (A) and without (B) an absorber present between the secondary toroidal inductor and a near field probe connected to a spectrum analyzer.

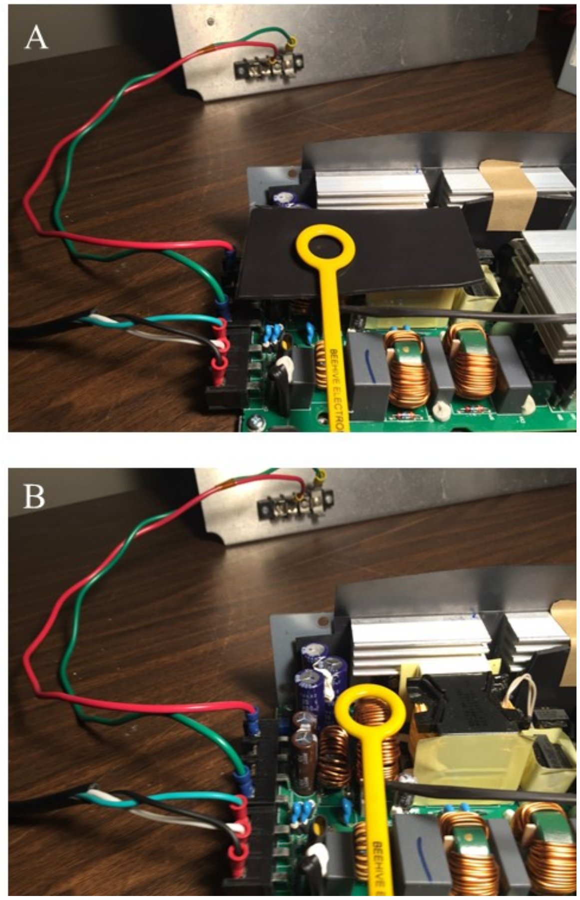

Figure 5. Power Supply Test Vehicle (A: With Absorber, B: Without)

Thermal Testing

Thermal conductivity was performed using ASTM D5470. This method was chosen because of the reliability and ease of use of the steady state test method [10]. Additional test methods, such as the laser flash method (ASTM E1461) are also available, but were not used in this study [11]. Previous work has shown good correlation between the two methods.

Materials Tested

A variety of materials were developed and evaluated for this study. Some of the materials were off the shelf items that were tested and others were specifically formulated for testing purposes. The samples that were tested for a general understanding of material properties and trends all had thermal conductivities above 1 W/m-K and demonstrated significant absorption in the 1-10GHz range. All of these materials were hybrid pads between 0.5 and 3mm composed of a polymeric matrix and a variety of thermally conductive and/or EMI absorbing fillers. For the representative materials used in the testing, pads were made at 1.5mm thickness with a thermal conductivity of 1 or 2 W/m-K and an EMI absorption level characterized as low, moderate or high.

RESULTS AND DISCUSSION

Performance Trends

The first part of this study focused on measuring the electromagnetic properties of a wide variety of materials and determining what overall correlations could be seen between the material composition, properties, and overall performance. Since thickness was expected to influence the absorption of a given material, pads were first tested to determine how the thickness influenced absorption and reflection. The results are shown in Figures 6 and 7.

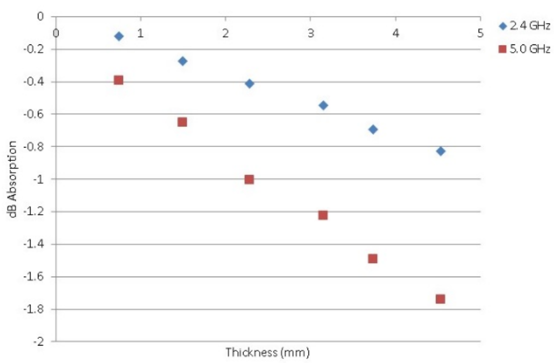

Figure 6. Variation in Absorption with Thickness

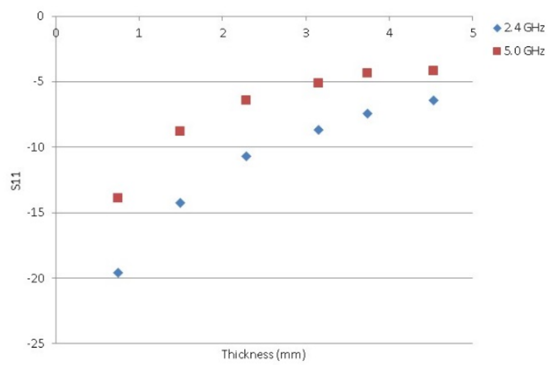

Figure 7. Variation in Reflection with Thickness

As can be seen, the absorption and reflection of a given pad both increase with thickness, but the reflection varies linearly while the increase in reflection slows at larger thicknesses. It should be noted that in Figure 7 the S11 parameter is plotted against thickness, so as the value approaches 0, more of the signal is reflected. Given the linear relationship between the absorption and thickness, the majority of the figures to follow will use absorption/length as a means to avoid any complications from variations in material thickness.

Figure 8 below shows how the absorption of a representative EMI absorber changes with the volume fraction of an absorbing filler.

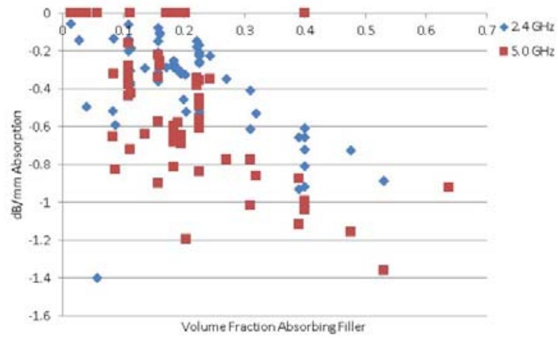

Figure 8. Variation in Absorption with Filler Loading

It can be seen that increasing the absorbing filler loading, in general, correlates nearly linearly with absorption. The absorption at 5.0 GHz is also higher than at 2.4 GHz, all of which are effects that would be expected based on the theoretical discussions presented earlier.

It is expected that including more absorbing filler would alter the magnetic properties of the pad itself, which is what is seen. This variation in the pad properties then correlates with the absorption as seen in Figure 9.

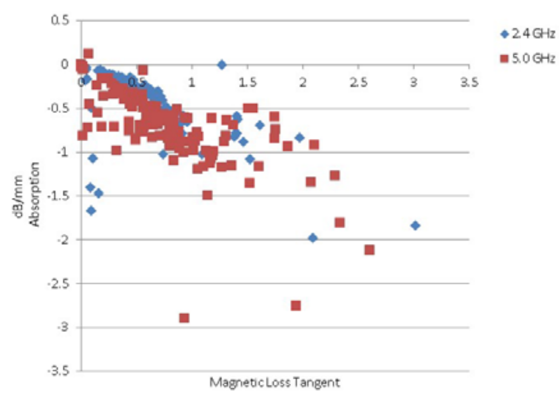

Figure 9. Variation in Absorption with Magnetic Loss Tangent

As the magnetic loss tangent of the material (μ''/μ') increases a similar increase in the energy absorbed is also observed.

Example Materials

In this section the performance characteristics of five representative materials will be presented to show how they behave at different frequencies. Figure 10 shows the absorption of these five materials.

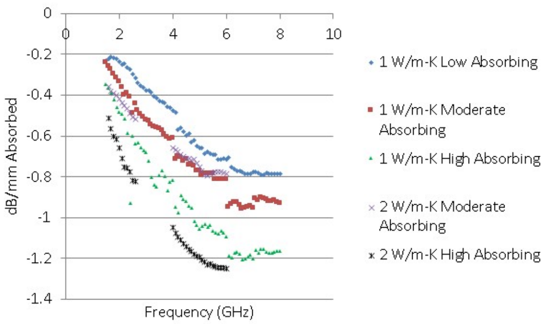

Figure 10. Material Variation in Absorption with Formulation

The materials absorb at varying amounts between 1.6 and 8.2 GHz, with an increase in absorption with frequency. It can also be seen that the thermal conductivity of a given material can be increased without changing the absorption and vice versa.

Figures 11-14 show the real and imaginary permeability and permittivity of the materials presented in Figure 9.

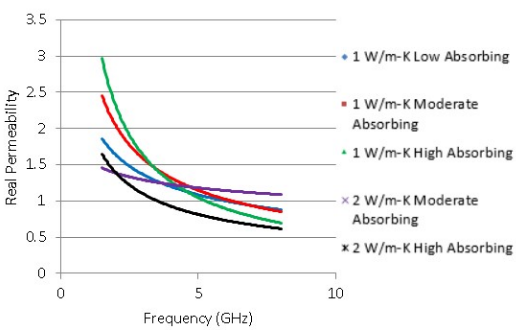

Figure 11. Real Permeability Variation with Frequency and Formulation

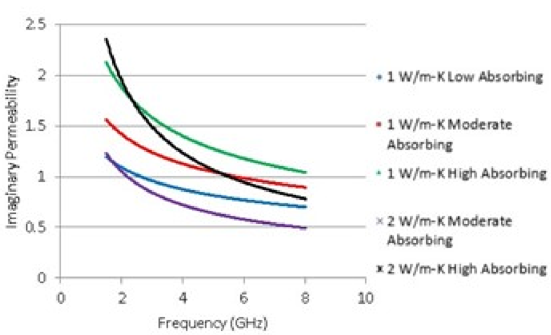

Figure 12. Imaginary Permeability Variation with Frequency and Formulation

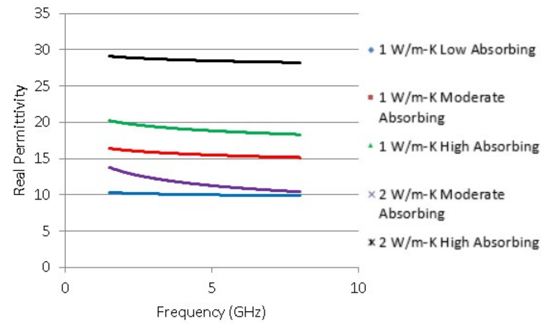

Figure 13. Real Permittivity Variation with Frequency and Formulation

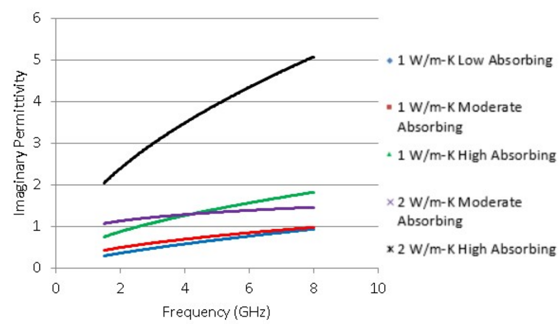

Figure 14. Imaginary Permittivity Variation with Frequency and Formulation

These figures show that permeability is a strong function of frequency, while permittivity, especially the real component, is not. The real component of the permeability also increases more quickly than the imaginary component as the frequency decreases. This change decreases the magnetic loss tangent of the material as the frequency decreases and results in less absorption.

The absorption decreases rapidly below 1 GHz as is shown in Figure 15.

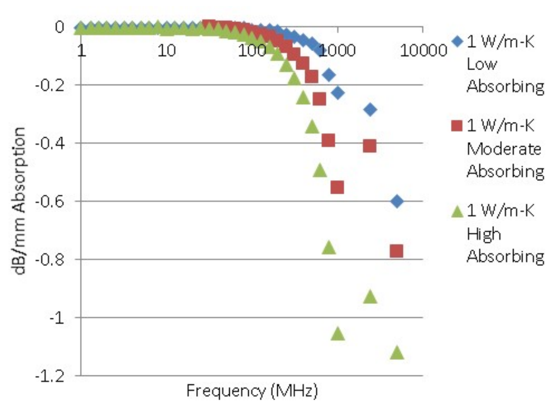

Figure 15. Absorption at <1GHz Variation with Formulation

The higher absorbing formulations perform better at <1 GHz than the lower absorbing formulations. However, once the frequency drops to 50-100 MHz virtually none of the signal is absorbed.

On the other end of the spectrum, above 8 GHz, these materials continue to absorb energy. In some cases the amount of absorption continues to increase. This data is presented in Figure 16.

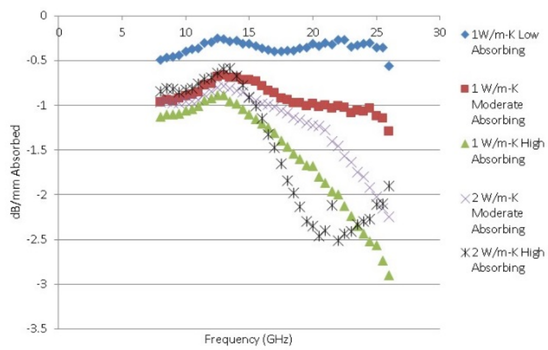

Figure 16. Absorption at >8GHz Variation with Formulation

In general, the materials with higher filler loadings (2 W/m-K, and 1 W/m-K high absorbing) showed an improvement in absorption as the frequency increased. The other materials showed close to no change in absorption as the frequency increased.

Application Testing
The first application test looked at the near field absorption of a pad on a 1.5 GHz chip loop antenna. Figure 17 shows the result of the test.

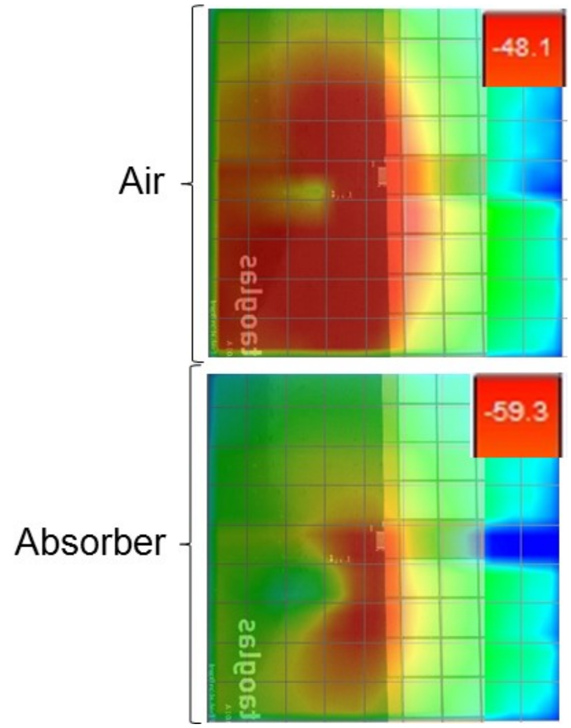

Figure 17. Signal Absorption on a Chip Loop Antenna at 1.5 GHz

The top scan in the figure shows the results with only air present and the bottom scan shows the results when the absorber was present. With the absorber present the amount of signal was significantly reduced.

In the second application test the ability of an absorber to reduce the signal in a power supply operating at 1kW with noise centered on 300 MHz was examined. As Figure 18 shows, the absorber significantly reduced the noise above 200MHz. The frequency ranges from 100MHz to 500MHz. The yellow curve is the measured signal with no absorber, the green curve is the measured signal with the absorber, and the blue curve is the measured signal with no current to the power supply.

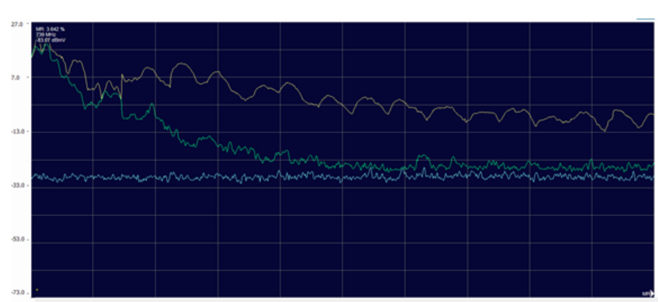

Figure 18. Absorption on 1kW Power Supply

CONCLUSIONS
It was shown that through the right combination of matrix and fillers materials could be formulated to conduct heat and absorb electromagnetic energy in the 1-10GHz range.

Increasing material thickness and magnetic loss tangent both significantly improved the amount of absorption for a given material. The material permeability was shown to affect performance through its variation with frequency. Application testing showed the utility of hybrid thermal/EMI absorbing materials. Overall, these materials will continue to find more use in electronics as devices shrink, speeds increase, and component densities grow.

FUTURE WORK

Future work is planned to further investigate applications testing. Additionally material formulation to target frequencies out of the 1-10GHz range is planned to expand the range of potential applications.

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