# Characterization of Double-Positive Metamaterials for Advanced Applications

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***Abstract*— A new type of metamaterial has been developed at the University of Missouri for use in pulsed power and high power microwave systems. These materials also have direct applications in dielectric-loaded components and nonlinear transmission lines. We present a double-positive metamaterial that incorporates high permeability, high resistivity nickel-zinc ferrite powers into a dielectric matrix. The ferrite powers were diagnosed using XRD and SEM analysis. A bimodal particle distribution was investigated with particles 5µm and 30nm in diameter. The 3D models of composites were constructed using a custom Monte-Carlo algorithm to investigate the effect of particle distribution and density on material electromagnetic properties. Simulations are compared with experimental results in order to validate the models. Power handling and dielectric strength were also examined with a 100kV, 60ns pulse derived from a PA-80. A maximum electric field of 309.50 kV/cm was measured before breakdown using 0.2cm thick disks, 2.54cm in diameter. Tests performed on the electromagnetic frequency response showed materials with near equal values of positive relative permeability and permittivity that were between 3.0-6.0 for frequencies between 200MHz and 1GHz. This work presents a statistical analysis of the dielectric strength, power handling, and electromagnetic response of the composites with varying particle distributions.**

## I. INTRODUCTION

The primary objective of this research effort was to further the minimization of HPM systems through development of new types of magneto-dielectric metamaterials. By leveraging recent breakthroughs in the area of high dielectric constant composites new materials were engineered to exhibit near equal values of permittivity and permeability while simultaneously withstanding extremely high peak power levels without destructive breakdown. The composite materials are a type of metamaterial due to the way in which the magnetic material is combined with a dielectric material within a composite at size scales smaller than the wavelength of the electromagnetic radiation encountered. A metamaterial approach is required to obtain the design flexibility in the material properties and a high power capability.

Such a material allows for the reduction of HPM systems by reducing the size of the antenna required by the system. Since the antenna size is directly related to the length of the electromagnetic wave that propagates through it, reduction of the wavelength in the antenna structure translates to a smaller antenna and an overall reduction in the HPM system. Significant antenna size reduction can be obtained by utilizing a material with extremely high permittivity or magnetic permeability [1]. This is shown by (1):

$$\lambda_m = \frac{\lambda_0}{\sqrt{\epsilon\mu}} \tag{1}$$

where $\lambda_m$ is the wavelength within the antenna structure, $\lambda_0$ is the free space wavelength, and $\varepsilon$ and $\mu$ are the permittivity and magnetic permeability of the antenna respectfully.
Increasing either $\varepsilon$ or $\mu$ independently of the other requires a decrease in the impedance $\eta$ of the antenna as shown by (2):

$$\eta = \eta_0\sqrt{\frac{\mu}{\epsilon}} \tag{2}$$

where $\eta_0$ is the free space impedance of 376.73 Ω [2]. This direct link between the wavelength within an antenna and its impedance means that both the permittivity and magnetic permeability must be increased such that the ratio between them remains fixed in order to reduce the antenna size while keeping the impedance fixed [1]–[4].

In order to address both the electromagnetic constraints and high dielectric breakdown needed in a HPM system, a magneto-dielectric metamaterial was investigated. A metamaterial made by imbedding magnetic particles into a high dielectric strength polymer allowed for independent adjustment of the electromagnetic parameters while also providing high breakdown strength and machinability. This work focused on how the particle distribution affected the electromagnetic and dielectric breakdown of the material.

## II. MATERIAL DESIGN

### A. Material Parameters

The proposed material needs to be able to withstand the application of high power as well as being highly machinable. It also needs to have near equal values of permittivity and magnetic permeability over as wide a frequency band as possible. To meet these requirements a variety of factors were taken into account. In terms of power handling, the dielectric breakdown of the material is considered. The material needs to be able to withstand fields of hundreds of kV/cm without destructive breakdown. Previous work has characterized a fully machinable composite material with high dielectric constants that have been designed for high power applications [8]. Those composites integrate $BaTiO_3$ in the hexagonal

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phase into a polymerized dielectric matrix. This approach was shown to produce composites able to withstand fields of between 120 kV/cm and 220 kV/cm while also demonstrating permittivity values between 100 and 120 [9], [10]. This same approach was adapted to the current research to create a metamaterial by substituting magnetic powder for $BaTiO_3$.

Ferrite was chosen as the magnetic inclusion due to its relatively high resistivity, magnetic permeability, and moderate permittivity [5], [6]. In particular Ni-Zn ferrite has been shown to have magnetic permeability values in the thousands, permittivity values in the twenties, and reasonably low losses at frequencies as high a 2 GHz [7], [8]. The low losses are due to the high resistivity preventing eddy current flow and the zinc atoms increasing the response time of the magnetic domains [9]. Such ferrites are not easily machined.

### B. *Binary Distribution*

Previous work in this area investigated how the dielectric and electromagnetic properties of a metamaterial were affected by changes in the Nickel to Zinc ratio within the alpha and beta sites in the ferrite lattice [10]. This research identified two specific ferrite compositions that produced metamaterial disks that demonstrated superior values of dielectric strength and electromagnetic frequency response [11]. Ferrite powder with a continuous distribution was utilized since it allowed for the production of material with the highest particle packing density.

A continuous particle distribution is created by selecting an upper an lower particle size that are both smaller than the starting particle size of your material. By high velocity ball milling, or a similar process, and repetitive particle sizing, it is possible to obtain a powder with particles only within the particle size range that was selected. While this distribution is relatively easy to create in the laboratory, it is rather difficult to control ratio of particle with a specific diameter that falls in the selected size range.

The current research effort expands on the previous work by utilizing powder with a binary, or two particle, distribution. Such a distribution allows for precise control of the volume ratio of a particle with a particular diameter. It was believed that this increase in the order of the particle packing arrangement would lead to a substantially greater dielectric strength than observed in previous experiments. By increasing the particle packing order, there is a more uniform mixing of dielectric binder material and ferrite. This allows for a more uniform spread of the electric field energy throughout the material.

The bi-modal distribution of maximum density that was chosen for this experiment was 90% by volume of particles 5 μm in diameter and 10% by volume particles 30 nm in diameter. The particle sizes ratio is based on the density of bulk ferrite, 4.7 g/cm3, and the size of the small filler particles were chosen to be 30 nm in diameter based on commercial availability. The size of the large and small particles were confirmed by using a scanning electron microscope to measure the Feret diameter.

### C. *X-Ray Diffraction Analysis*

Two compositions of Ni-Zn ferrite were used in this study and were given the names of MMU1 and MMU3. X-ray diffraction (XRD) was used to confirm the ratio of Nickel to Zinc as well as the phase of the ferrite lattice. Figs. 1 and 2 show data obtained for MMU1 and MMU3 respectfully using a Rigaku XRD.

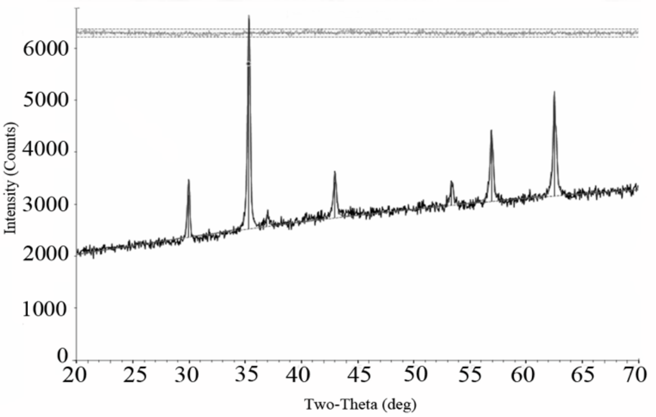

Fig 1: X-ray diffraction of MMU1 Ni-Zn ferrite

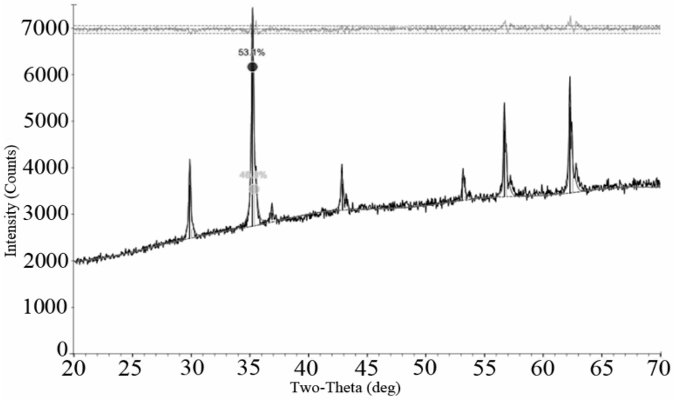

Fig 2: X-ray diffraction of MMU3 Ni-Zn ferrite

Using spectrum matching software to compare the results shown in Figs. 1 and 2 it was possible to confirm that both MMU1 and MMU3 both belonged to the space group cFd-3m(227) indicating a cubic phase for both ferrites. It was also confirmed that MMU1 had a lattice with a majority of the Iron substitutions being Nickel and MMU3 had a majority being Zinc.

## III. 3D SIMULATION RESULTS

In order to aid in the design and analysis of the metamaterial composites, a custom Monte Carlo code was developed. This code allows for rapid collection of density and electromagnetic data from a large number of simulated bi-modal disks. The results of these simulations were used to provide indirect evidence that a true bi-modal distribution was present in experimentally tested disks as well as help build a physical model of how electromagnetic energy permeates throughout the disks and effects the breakdown mechanics.

The presence of a true bi-model distribution in the experimentally produced disks was indirectly investigated by comparing the theoretical and experimentally obtained average densities of a disk. This check is important since a mishandling of any of the experimental parameters involved in the disk manufacturing process could result in a drift in the particle distribution. Fig. 3 shows a cross section of a simulated material utilizing a bi-modal distribution. Averaging a large number of simulations allowed for the calculation of the theoretical average density of $3.4 \text{g/cm}^3$ for a bi-modal distribution. This number agrees, to within uncertainty, with the experimentally determined average density of $3.2 \pm .2 \text{ g/cm}^3$ for metamaterial disks.

The simulations also provide a look at the electric field density within the simulated material. This field density is used to provide insight into how and where breakdown can be expected in physical disks. Fig. 4 shows the results of a electromagnetic simulation of the disk shown in Fig. 3. The simulated fields are projected onto a 2D plane for a cross section of the disk. The results of the simulations show that the electric field is strongest at the corners of the material where it is on average 57.2% larger than the average internal field energy. Therefore, breakdown is expected first at the electrode edge and this is observed experimentally when electrodes are applied to the material surface and tested. When the disk surface and electrode edges are smoothed to reduce triple points, breakdown is only experimentally observed in the bulk of the disk.

Simulations show that the second highest fields are calculated around the 5μm particles where the field energy is on average 42.9% larger than the average internal field. The largest internal fields are observed when there are collections of tightly spaced 5μm particles and the lowest internal fields are observed when the 5μm particles are separated by a large number of nanoparticles. The large volume difference between the large and small particles means that there is a significant network of dielectric binder between each of the larger particles. A bi-modal distribution is therefore believed to allow for a minimization the internal electric field density while maximizing the particle density. This hypothesis was tested by comparing breakdown statistics of metamaterial disks having a bi-modal and continuous distributions.

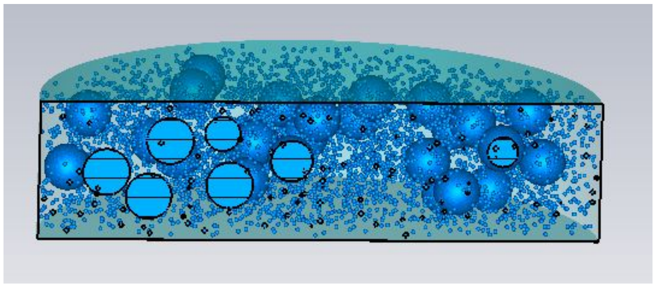

Fig 3: Cross section of simulated metamaterial

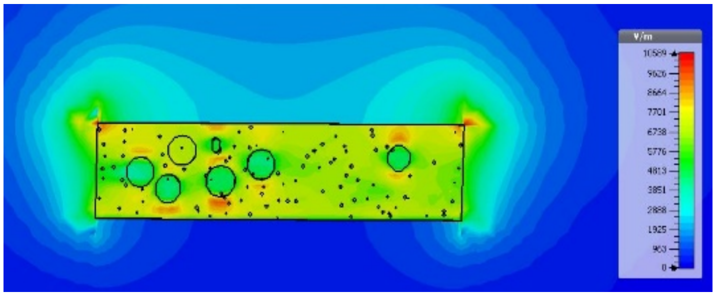

Fig 4: 2D representation of simulated electrometric field

## IV. DIELECTRIC STRENGTH

An important factor in determining the survivability of a material for use in a high power antenna system is its dielectric strength. The ability of a material to withstand extremely high electric fields is often a limiting factor in the power handling capability of these types of antennas. Also, since the desired application is to hasten the development of compact systems in which the energy density is high as compared to the system volume, measurement and characterization of the material's ability to withstand such fields is of great interest. There are a number of different methods for evaluating the dielectric strength of a material. Due to the fast rise time of the applied voltage seen in high power antennas it was decided that the composite material needed to be tested under pulsed conditions.

Table I shows the average breakdown voltage, average electric field, and maximum electric field measured during the tests for both a continuous and bi-modal distribution. The results show that the average breakdown voltage for MMU1 and MMU3 with a bi-modal distribution have increased by 68\% and 88\% respectively when compared to disk made with a continous distribution [11], [12]. This substantial increase in voltage hold off was predicted by the results of the Monte-Carlo electormagnetic simulations and is attributed to the increased degree of particle order in the bi- modal metamaterial composite. The use of an ordered distribution with fixed particle sizes allows the electric field energy to spread more evenly throughout the composite, acheiveing higher breakdown voltages.

TABLE I: AVERAGE BREAKDOWN VOLTAGE AND AVERAGE AND MAXIMUM ELECTRIC FIELD SUSTAINED FOR .2 CM THICK BIMODAL MMU1 AND MMU3 COMPOSITES

| | Average Breakdown Voltage [kV] | Average Electric Field [kV/cm] | Maximum Electric Field [kV/cm] |
|---|---|---|---|
| MMU1 Continuous | 32.76 | 163.80 | 167.29 |
| MMU3 Continuous | 29.79 | 149.95 | 152.44 |
| MMU1 Bi-modal | 55.11 | 275.55 | 294.63 |
| MMU3 Bi-modal | 56.59 | 282.95 | 309.50 |

## V. ELECTROMAGNETIC FREQUENCY RESPONCE

In order to calculate the frequency dependent relative permittivity and relative magnetic permeability of the composites, an algorithm described by Nicolson, Ross, and Weir was used [13], [14]. As part of this algorithm scattering parameters $S_{11}$, $S_{21}$, $S_{22}$, and $S_{12}$ for the material are measured. A Fourier transform is used to convert these parameters to their frequency dependent forms which are then used to calculate the frequency dependent relative permittivity and relative magnetic permeability [13], [14]. Tested disks utilized a toroidal geometry with an outer diameter of .7cm and inner diameter of .3cm. A disk length of .7cm was selected to reduce the error in the scattering parameter values [15].

Figs 5 shows that using a bimodal distribution results in an average permittivity of 7.3 and 8.8 for MMU1 and MU3 respectively. These values are higher then what was observed in other studies [11]. This increase is explained by the increased order of the bi-modal distribution. This order leads to increased polarization from a more even dispersal of the electric field energy. Fig. 6 shows that electric loss tangent of the material is within acceptable ranges between 200 MHz and 1 GHz.

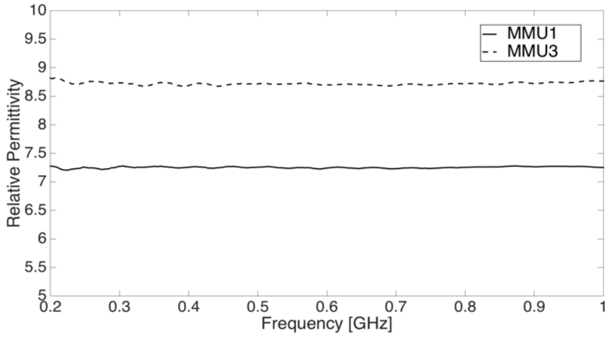

Fig 5: Relative permittivity as a function

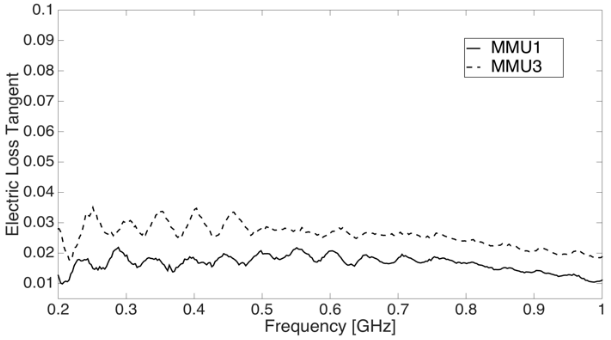

Fig 6: Electric loss tangent as a function of frequency

On the other hand, a decrease in the magnetic permeability as compared to previous studies was also observed [11]. This is shown by Figs 7 and 8 and was expected since the bimodal distribution is less dense than a continuous distribution, reduceing the magnetic particle content. Figs. 7 and 8 show the relative magnetic permeability and magnetic loss tangent respectively. The magnetic properties of this material resemble that of bulk ferrite in that as the frequency increases, the magnetic permeability decrease while the magnetic losses increase proportionally with frequency.

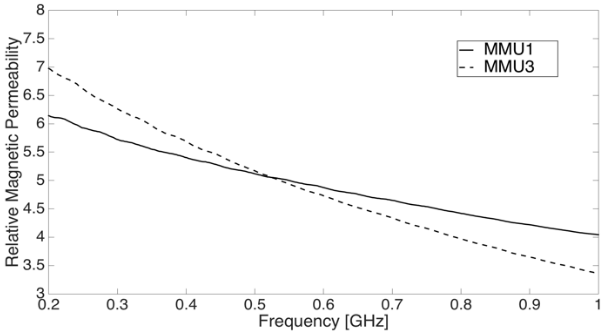

Fig 7: Relative magnetic permeability as a function of frequency

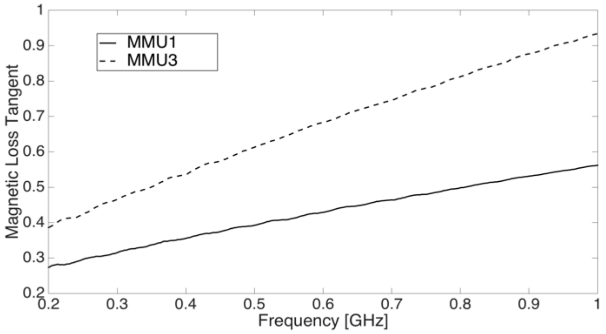

Fig 8: Magnetic loss tangent as a function of frequency

## VI. CONCLUSION AND FUTURE WORK

This work evaluated the effect of implementing a binary particle distribution into ferrite based metamaterial composites designed for HPM systems. A custom Monte Carlo 3D computer code was developed for verification that a bi-modal distribution was obtained. This code was also used to build a physical model of the breakdown mechanics. The dielectric strength was tested under pulsed conditions and the results show that the average breakdown voltage for MMU1 and MMU3 with a bi-modal distribution have increased by 68\% and 88\% respectively when compared to disk made with a continous distribution. This substantial increase in dielectric strength can be explained by the physical model devleloped with the electormagnetic simulations, which suggests the increase is attributed to the increased degree of particle order in the bi- modal metamaterial composite. The electromagnetic frequency response of the bi-modal metamaterial was also investigated. It was observed that the ratio of the permeability and permittivity was near unity up to about 500 MHZ. When compared to bulk ferrite, the metameterial has the advatage of independently adjusting the electormagnetic properties.

Future work will look at the development of a more sophisitcated elecromagentc model based on mixing laws. The electormagnetic propertties of the material will be further incresed by using a three particle distribution along with alignment of the magnetic domains during polimerization. It is expected that the magnetic losses can be further reduced by the magneic particles.

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