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ADVANCED MULTIFUNCTIONAL MATERIALS FOR HIGH SPEED COMBATANT HULLS

FINAL TECHNICAL REPORT

1.0 Abstract

In this ONR funded project investigators at the University of Delaware's Department of Electrical and Computer Engineering and Center for Composite Materials developed a new additive manufacturing process for realizing composite materials with prescribed RF properties over a broad frequency range.

The major accomplishments of this effort were:

- We developed a synthesis method for creating high dielectric constant inks/pastes that are well suited for screen printing and micro-dispensing. We validated those properties experimentally.
- We developed a synthesis method for creating magnetic inks/pastes that are well suited for screen printing and micro-dispensing. This included processes for synthesizing the magnetic nanoparticles. We validated those properties experimentally.
- We developed a scalable and cost effective methodology for creating structural woven fabrics with prescribed RF loss properties by screen printing patterns of resistive inks. These materials would then form the backbone of a new method for making radar absorbing structures.
- We developed a scalable and cost effective methodology for creating armored materials (i.e. high molecular weight polyethylene or Spectra Shield) with prescribed RF loss properties by screen printing patterns of resistive inks.
- We derived a Debye based effective media model that closely matches experimental results.
- We worked closely with our partners at the Naval Surface Warfare Center, Carderock Division, to transition these new materials to practical applications of interest to the Navy.

2.0 Introduction

Currently small boat combatant design focuses primarily on speed and maneuverability. It would be advantageous to expand these capabilities to include reduced radar cross section, enhanced survivability to blast and ballistic threats for both the structure and warfighters.

In this effort investigators from the University of Delaware along with Navy partners at the Naval Surface Warfare Center, Carderock Division, developed the material building blocks necessary to realize hull materials for small boat combatants that combine structural properties with integrated radar absorption and enhanced ballistic protection. Specifically, we explored the use of additive manufacturing methodologies to develop new multifunctional materials that can be manufactured in a flexible, scalable and cost effective manner. These new materials and processing methods will be part of a library of core material building blocks that can be optimally combined in a stackable layup to produce the next generation of multifunctional hulls.

The specific objectives of this effort were to; 1) create computer design tools that can be used to "engineer" the electromagnetic properties of traditional structural and ballistic naval materials over a broad frequency range, 2) develop scalable manufacturing methodologies using additive manufacturing that can be used to realize structural and ballistic panels with engineered electromagnetic properties and 3) demonstrate manufacturability of these solutions by fabricating and characterizing flat test panels.

3.0 Technical Approach

Currently, most high speed combatant hulls are traditional sandwiched core designs constructed from a foam or balsa wood core sandwiched between two composite face sheets. Current methods to augment these structures with ballistic capabilities employ bolted outer panels. In this approach arrays of small panels, made typically from metal, carbon, glass or high strength polymer fibers, are bolted onto the outer surface. One clear disadvantage of this approach is the large (>100%) increase in both size and weight. Currently, the use of outer panels constructed from high strength polymer fibers, such as Dyneema or Spectra, has shown the most promise in adding ballistic performance while minimizing additional weight and should be considered the state of the art in structural/ballistic hulls.

Similar to the approach taken for adding ballistic capabilities most radar absorbing hulls are constructed by adding layers of radar absorbing materials (RAM) treatments to the outer surfaces of a traditional hull design. As in the previous case this adds additional size and weight in addition to introducing new maintenance issues due to weathering of the RAM treatments. **There are currently no examples of hull materials, or any military composite material for that matter, that combines structural, ballistic and radar absorbing functionalities.**

The technical approach we used was to exploit and combine recent advances in lightweight composite materials and additive manufacturing methods. Specifically, we employed scalable screen printing to print patterns of functionalized custom inks and pastes to composite materials. The proposed effort was modeling and simulation driven guiding the selection of appropriate composite materials, inks, additives and printable patterns. The end goal was to create design methodologies (illustrated in Figure 1) that can be followed to produce composite materials with well-defined electromagnetic, structural and ballistic properties.

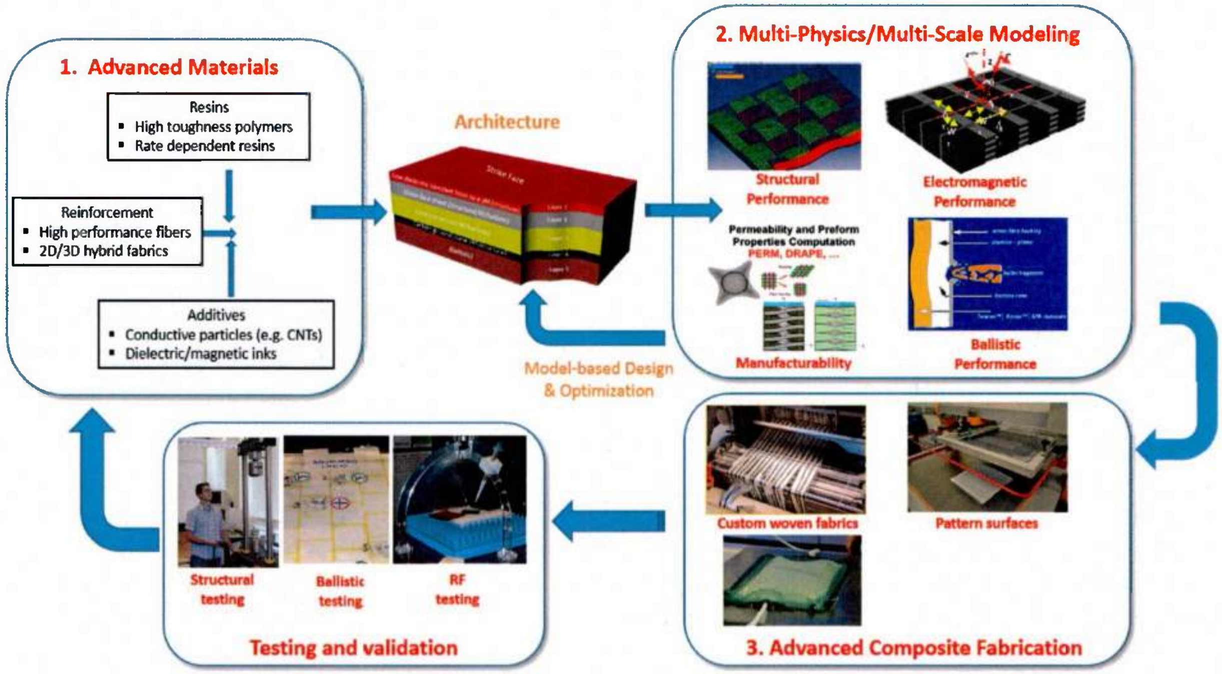


Figure 1. General technical approach for integrated optimized design methodology that leverages recent advances in materials, computer modeling and additive manufacturing methods.

4.0 Methodologies

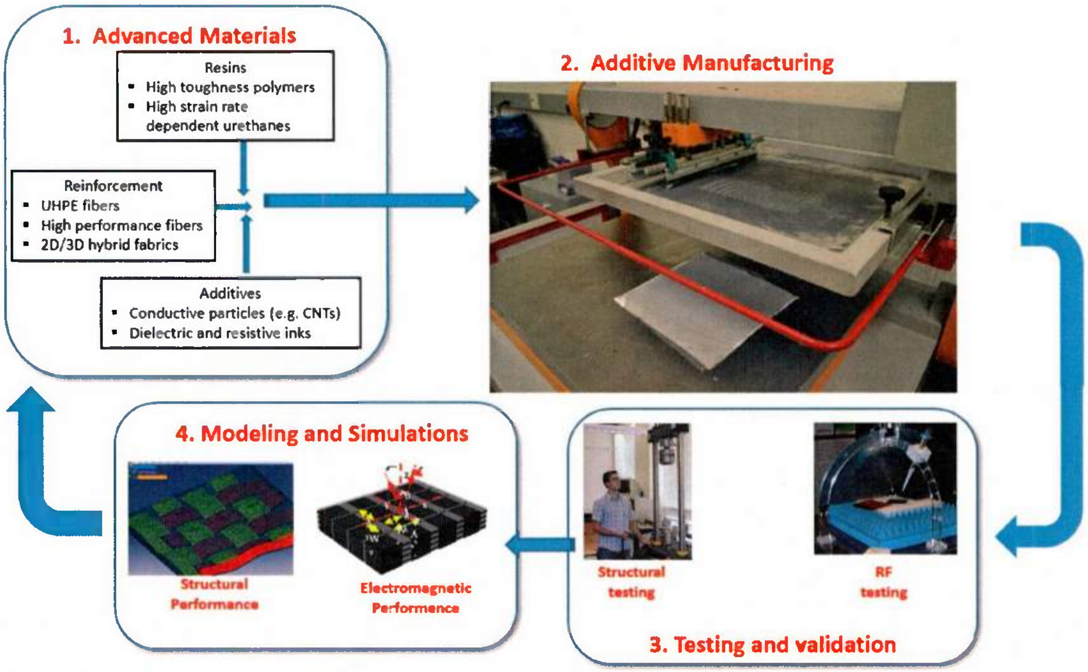


Figure 2. Overview of general methodology.

An overview of the methodology used during this study is shown in Figure 2. The report is broken into the several key blocks shown in Figure 2. Namely; (1) Base materials, (2) Additive manufacturing methods, (3) Modeling and simulations and (4) Testing and validation.

I. Base Materials

To realize a multifunctional hull material that minimizes weight we leveraged a number of advances in new composite materials. These materials, in addition to standard woven glass and carbon based composites, formed a set of base materials. Specific materials we explored during this project are listed below.

- <u>Woven Glass Fabrics and Kapton Films</u> – woven glass fabrics are a key building block of many composite structures. Kapton, or polyimide films are a common dielectric substrate used for printing electronics. Specifically we used a 6781 s-glass 8HS 8oz S-glass fabric and Dupont 2mil Kapton film.

- High Strain Rate Polymer Composites –Dyneema HB26 or Spectra Shield, are composite materials made from ultra-high-molecular-weight (UHMW) polyethylene fibers embedded within a high strain rate dependent urethane matrix (such as polyurea). Layers of this material are then stacked and fused into a composite structure under heat and pressure. This results in a material that has very good ballistic properties yet is much lighter than traditional armor. As a result these materials have been previously used in a variety of ballistic applications including combat helmets. Moreover, polymer composites, such as Dyneema, have attractive electromagnetic properties (e.g. low loss over a broad range of frequencies) which can be modified to be part of a radar absorbing structure. We explored the use of these materials as part of a multifunctional core material that combines ballistic, RAM and some structural characteristics. Specifically we used Honeywell Spectra Shield 2 SR-3124.

- Electromagnetic Additives - The ability to develop unique inks and pastes with attractive EM properties was a critical aspect of this effort. Polymer-based ink composition can be tailored using a variety of electromagnetic fillers to achieve the desired viscosity and particle loading for the target electromagnetic properties. We explored several new electromagnetically functional inks that included additives such as carbon powders, high dielectric constant powders and nano-ferrites. Each of these is described below.

A. Resistive Inks

Carbonaceous particles were suspended in an ink to tailor the absorption properties of the deposited material. In order for the ink to provide enough attenuation within the desired frequency range, a selection process of the carbonaceous particles and ink was completed. The carbonaceous particle type that was selected for this research was carbon black.

To create in-house high loss tangent inks, Regal 400R Carbon black particles were obtained from Cabot Corporation and sheer mixed with a plastisol ink. We used type types of plastisols. Specifically, International Coatings 10 NP Clear Multi-Purpose Plastisol Ink and Atlas Screen-Supply Company Plastisol Ink. These mixed inks were determined to be too viscous to be used for screen printer. We also evaluated multiple commercial inks. These were; 1) BARE Electric Paint, 2) YSHIELD HSF54, and 3) Dupont 7082 Resistor Ink. The inks were tested by hand rolling a layer of the different inks onto a Kapton film. The dielectric properties of the samples were then measured in an anechoic chamber. The Dupont 7082 Resistor Ink was determined to be the most attractive. It has an ideal viscosity for screen printing and the microwave loss properties were in the right range for absorber design. For the remainder of this project we utilized the Dupont 7082 as our resistive ink.

B. High Dielectric Constant Inks

Unlike the resistive inks a screen printable high dielectric constant ink is not available commercially. Consequently, we developed an in-house process. A resin-based high dielectric-composite was fabricated using commercially available $BaTiO_3$ powders as a filler material combined with EPON™ 8132 and

EPIKURE™ 3226 resin system. The resin was selected for its EM properties (εr ≈ 2.5, and tanδ ≈ 0.001) and capability or high volumetric loading. Samples of $BaTiO_3$/EPON were created by adding filler to the resin in order to make volumetric loaded fractions of 10 – 40 % composite samples with favorable electromagnetic and mechanical properties (i,e, high permittivity, low loss tangent, high flexibility). The samples were mixed using a shear-mixing apparatus to promote uniform particle distribution, degassed in a vacuum chamber to remove excess air bubbles, poured into sample molds and cured at 100 °C for two hours. Large panels were made that were approximately 15 cm x 15 cm x 0.5 cm and measured using a focus beam free space measurement chamber, where the transmission parameters were measured and computed into the relative permittivities and dielectric loss tangents using a custom rigorous-coupled wave (RCW) algorithm.

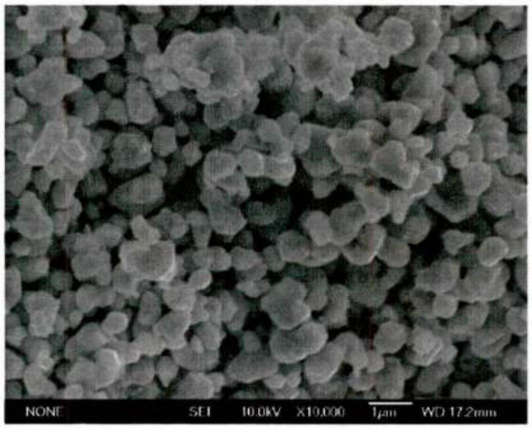


Figure 3. SEM micrograph of BaTi particles

C. Magnetic Inks

Magnetically loaded inks that are well suited for additive printing are also not available commercially. As a result we developed our own in-house process for creating magnetic nano-particles and suspending them within a polymer matrix. We employed two different methods for synthesizing the magnetic nanoparticles. Namely, polyol reduction and a solid-state ceramic method. These are described below.

Polyol Reduction

For the formation of magnetic Fe_3O_4 particles, 0.01 mol $FeCl_3{\cdot}6H_2O$ was added to the combined solution of 0.05 mol NaOH in 200 mL of EG at reflux. The following reaction occurred, where:

$$EG + NaOH + FeCl_3 \xrightarrow{\Delta} Fe_3O_4 + NaCl + EG + H_2O$$

After the specified reaction time of 6 hr, the solution was cooled to room temperature and washed with de-ionized (DI) water to separate the EG byproducts, in this case, NaCl from the magnetic particles. This material was very easy to separate by using an NdFeB magnet, indicating that the crystallinity of the material is good enough to support room temperature magnetization. The particles were then dried overnight in an oven at 60 °C in air to produce black powder and were crushed using an agate mortar and pestle. The materials were characterized using XRD, SEM, and VSM.

Solid-State Ceramics Method

As an alternative to the relatively low-yield nanoparticle synthesis, a conventional solid-state ceramics processing method was also used to develop $Ni_{0.5}Zn_{0.5}Fe_2O_4$ particles. Oxide precursors of 0.05 mol NiO, 0.05 mol ZnO, 0.10 mol and Fe_2O_3 were mixed together using water to form a slurry and then dried. This oxide powder mixture was finely ground using an agate mortar and pestle, then placed in an Al_2O_3 crucible and calcined at 1000 °C for 2 hrs with a 2.5 °C/min ramp rate in a tube furnace. The following reaction occurs, where:

$$ZnO + NiO + Fe_2O_3 \overset{\Delta}{\rightarrow} Ni_{0.5}Zn_{0.5}Fe_2O_4$$

After cooling down to room temperature, it is immediately apparent that some of the powders sintered together and formed aggregate that are sub-millimeter in size, with a slight reduction of mass (approximately ~15 %). The material was ground using an agate mortar and pestle, but unfortunately did not reach our size threshold and required additional grinding via milling machine. A stainless steel jar and yttria-stabilized zirconia (YSZ, purchased from Inframat Advanced Materials) 5.0 x 5.0 mm cylinders as milling media were selected due to the relative hardness of the materials. The MDM were added into the jar with a powder (g) media (g) ratio of 1:10 and put onto a tumbler mill for 24 hr. The tumbler mill was selected due to the relatively low kinetic energy resulting in gentle grinding of the media without contamination from the milling jar, as opposed to a planetary mill or high-speed shaker mill, where the extremely high kinetic energy would undoubtedly contaminate the MDM with excess Fe, which could potentially increase conductivity and result in detrimental high-frequency loss characteristics. Following the milling procedure, the MDM were characterized using XRD, SEM, and VSM.

Magnetodielectric Composite Materials

A resin-based MDM-composite was fabricated using the synthesized MDM's as a filler material combined with EPON™ 8132 and EPIKURE™ 3226 resin system. The resin was selected for its EM properties ($\varepsilon_r \approx 2.5$, and $\tan\delta \approx 0.001$) and capability or high volumetric loading. Samples of Fe_3O_4/EPON and $Ni_{0.5}Zn_{0.5}Fe_2O_4$/EPON were created by adding MDM's to the resin in order to make volumetric loaded fractions of 10 – 40 % composite samples with favorable electromagnetic and mechanical properties (i,e, high permeability and permittivity, low loss tangent, high flexibility). The samples were mixed using a shear-mixing apparatus to promote uniform particle distribution and then poured into sample molds and cured at 100 °C for two hours. Discs samples with a dimensions of 20 mm in diameter, and 2 mm thickness were made to measure the high-frequency complex permittivity and dielectric loss tangents using an impedance analyzer. After these measurements were made, a center hole was drilled out to make a one-turn inductor, where the frequency dependent complex reflection coefficient was measured using the vector network analyzer.

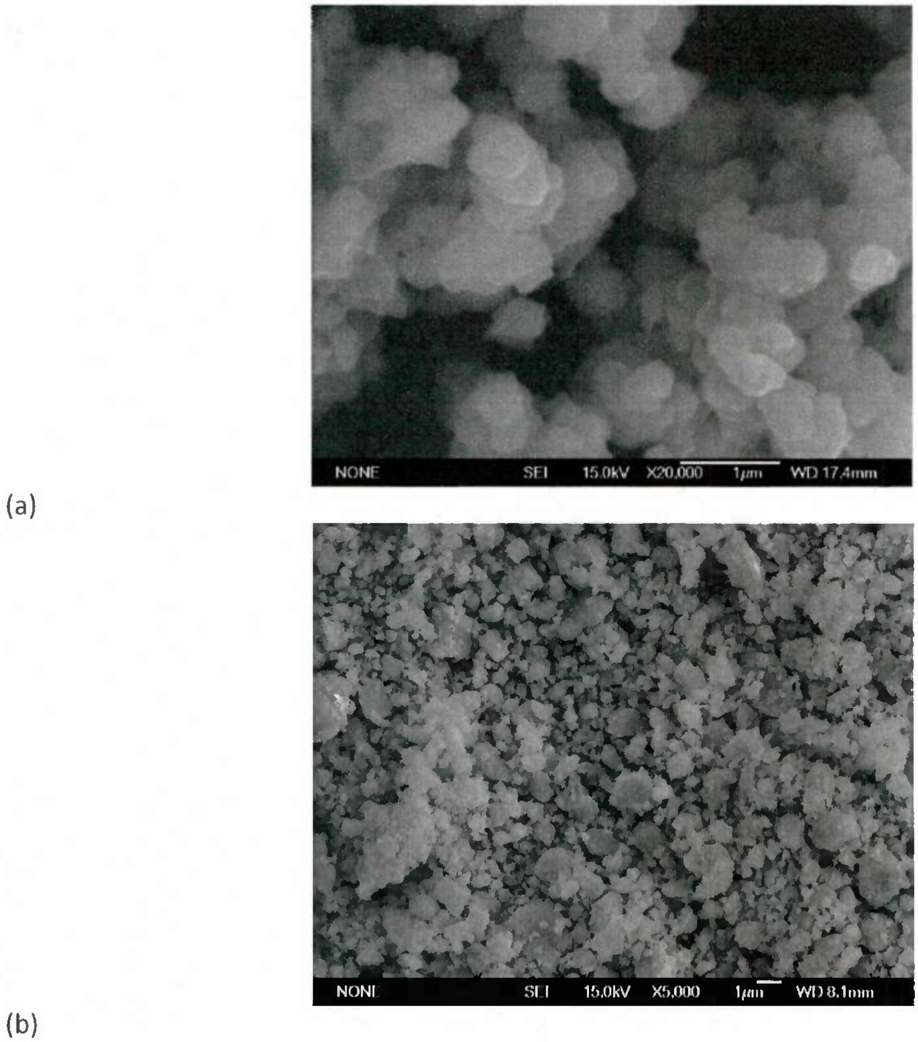


Figure 4. (a) SEM micrograph of Fe3O4 magnetic nanoparticles, (b) SEM micrograph of $Ni_{0.5}Zn_{0.5}Fe_2O_4$ magnetic particles

II. Additive Manufacturing Methods

To tailor structural, ballistic and electromagnetic properties within a composite required exploring new manufacturing methods. This has been a core area of research for us over the last five years and resulted in several unique methods for integrating electromagnetic functionality into structural and ballistic composites. In this project we explored the use of screen printing and micro-dispensing.

SCREEN PRINTING

Screen printing is an additive manufacturing method that utilizes a mesh screen, a flood, and a squeegee, as seen in Fig. 5. The mesh screen that was used contains a desired geometrical pattern that was deposited onto the substrate. When the flood is actuated, it deposits ink across the surface of the screen, the screen is then lowered to a snap-off height above the substrate, and the squeegee actuates to deposit the desired pattern. The substrate is then heated to cure the deposited ink. This process allows for a designed pattern to be repeatedly deposited onto multiple substrates in a short period of time. This feature is appealing for large volume fabrication of repeated designs that need to be deposited onto multiple substrates.

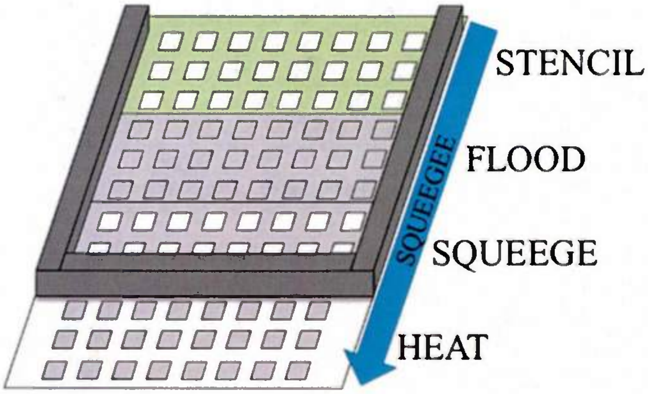


Figure 5. Screen printing process

The screen printer used during this project is a Grafica Flextronica Nano-Print Plus model number GF-2228-N.P.P, pictured in Fig. 6. Screens were designed using Rhino CAD and purchased from UTZ manufacturing. The screen frames used were 29 inch by 29 inch frames with a non-inset screen. The screen had a 28.5 degree stretch angle with a 325 mesh that had a width of 0.0011 inches and a 0.001 inch emulsion thickness. The screen printer itself has adjustments to fit screens of multiple sizes and the capability of incorporating multiple snap-off heights. The screen printer utilized a standard squeegee and flood bar, which were attached to an actuating motor. The flood and squeegee have fine adjustments that allow the user to adjust the position of the flood or squeegee. The screen printer has settings to flood, squeegee, lower the screen, and raise the screen. The squeegee and flood have a speed adjustment to allow for a slower snap-off.

Figure 6 Grafica Flextronica Nano-Print Plus

Screen Printer Modifications

Through experimentation the screen printer required a few modifications in order to properly deposit the desired patterns reliably. The first modification was to the squeegee, pictured in Fig. 7. The squeegee is made of a chemical resistive polymer that is held in place by a clamp. In order to seat the squeegee properly, the squeegee bar needed set screws to be inserted to apply equal pressure across the squeegee so that the print edge of the squeegee was flush with the surface of the screen. The second necessary modification was to create a heat box that could provide a surface cure to the printed inks, pictured in Fig. 7. The design of the heat box was necessary to avoid curing of ink within the screen mesh. With the use of a heat box, the heat was able to be applied directly where needed. The third and final modification was to incorporate a roll-to-roll system, pictured in Fig. 7. This system was implemented by attaching a rolling bar to the front and back of the screen printer. The roller was tested and successfully printed a sixteen foot section of continuous printed substrate. These modifications allowed for a more reliable and repeatable screen printing process.

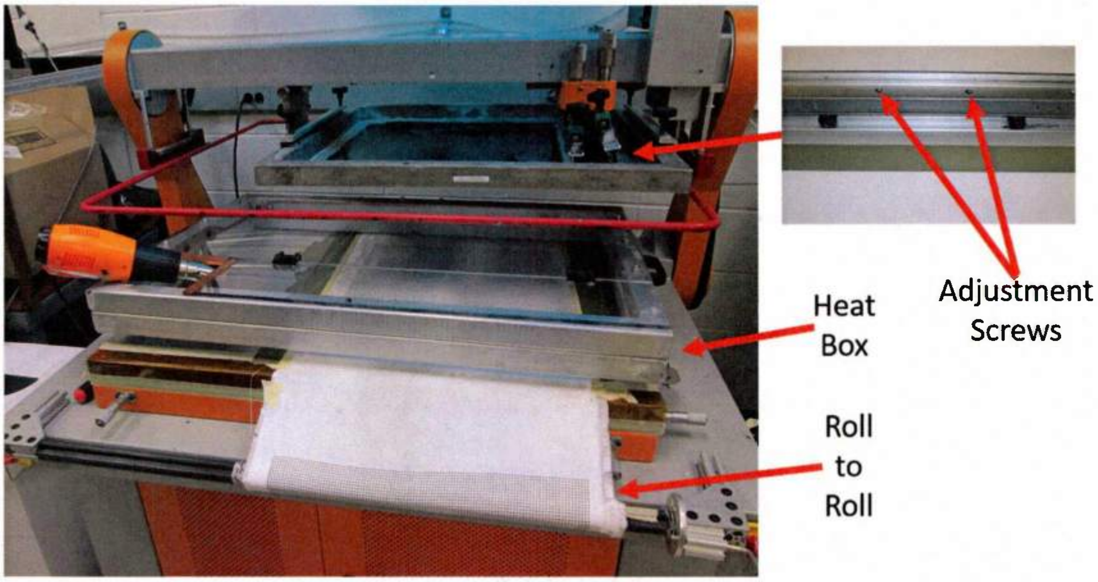


Figure 7. Screen printer modifications

MICRO-DISPENSING

Micro dispensing is a process of additive manufacturing that utilizes a dispensing head to precisely deposit a material. The micro dispensing system that was used in this research was an nScrypt 3Dn-300, pictured in Fig. 8. The system is capable of utilizing two different types of dispensing heads for depositing a wide variety of materials. The implementation of two printing heads allows for the printing system to toggle between printing two materials at once. These materials may also be swapped out mid print in order to incorporate a varying properties within one structure.

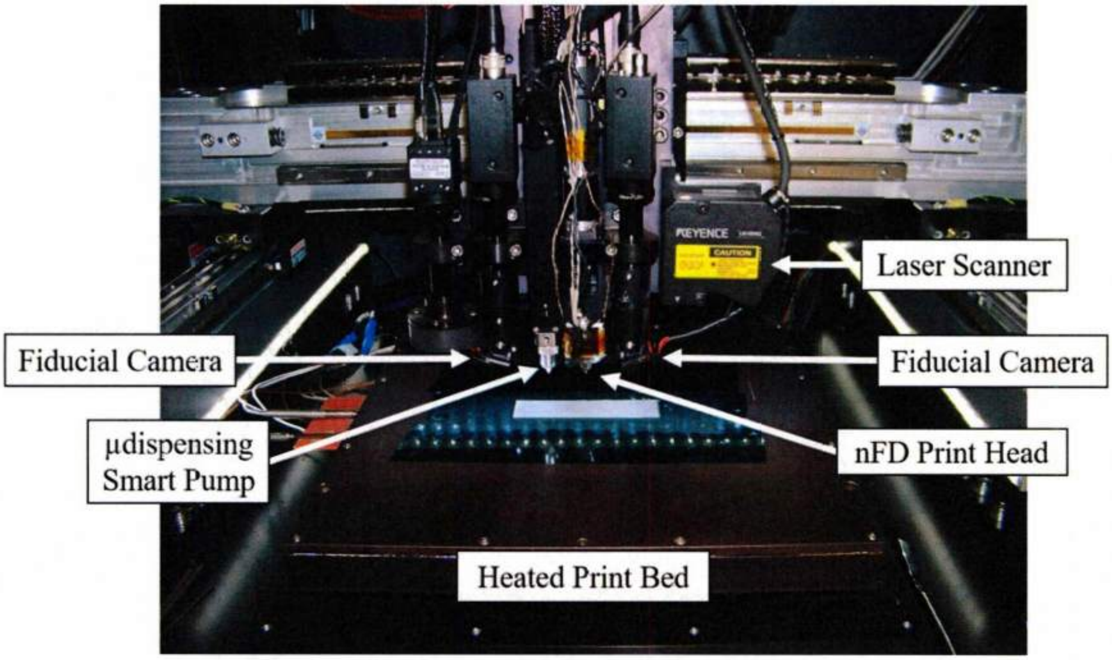


Figure 8 nScrypt 3Dn 300

The first dispensing head is a micro dispensing smart pump that utilizes pneumatic pressure to extrude material from a syringe to a dispensing tip at a constant rate. The second dispensing head is a fused deposition modeling (FDM) print head that is used to print thermal plastics. The print heads are capable of producing 25µm lines at a rate of 300mm/s and the stages are positionally accurate up to 1µm. The nScrypt is also equipped with a laser scanner that allows the user to scan a surface, so that the nScrypt can provide a constant print on a curved surface. The ability to scan a part and calibrate to any surface allows for precise deposition of material onto most substrates. In addition to this, the ability of the nScrypt to vary the pressure and valve opening of the smart pump allows the micro dispensing extrusion process to print a wide variety of viscosities varying from 0-1,000,000 cps. The smart pump was used for deposition of Dupont 7082 Resistor Paste and Dupont CB028 Silver Conductive Ink, and the FDM print head was used to print a polycarbonate thermal plastic.

5.0 Results

The results from this effort are broken down into three categories based on the nature of the ink used. Specifically, (1) high dielectric constant loaded composites, (2) magnetically loaded composites and (3) resistively loaded composites.

A. Results on Additive Manufacturing of High Dielectric Constant Composites

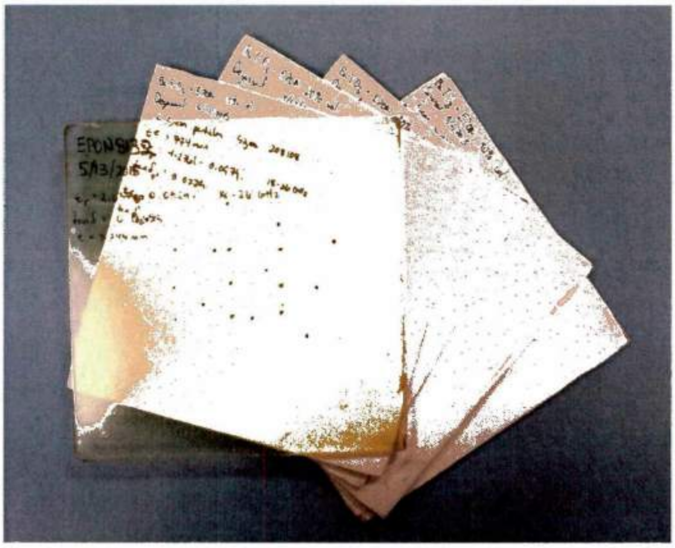


Figure 9. Additively manufactured high dielectric constant plates using the custom high dielectric constant pastes.

Using the custom high dielectric constant inks described earlier we fabricated a number of plates of various % loading to calibrate the process. The % volume loading of $BaTiO_3$ varied from 0% to 40%. Above 40% we found that the paste became too viscous to print reliably. The permittivity of the samples were measured using a free-space material measurement system from 18-28 GHz. The results are given in Figure 10 and Table #1. We were able to achieve using this process dielectric constants that varied from $\varepsilon_r=2.8$ (value of the resin without loading) to $\varepsilon_r=14.3$ at 40% loading.

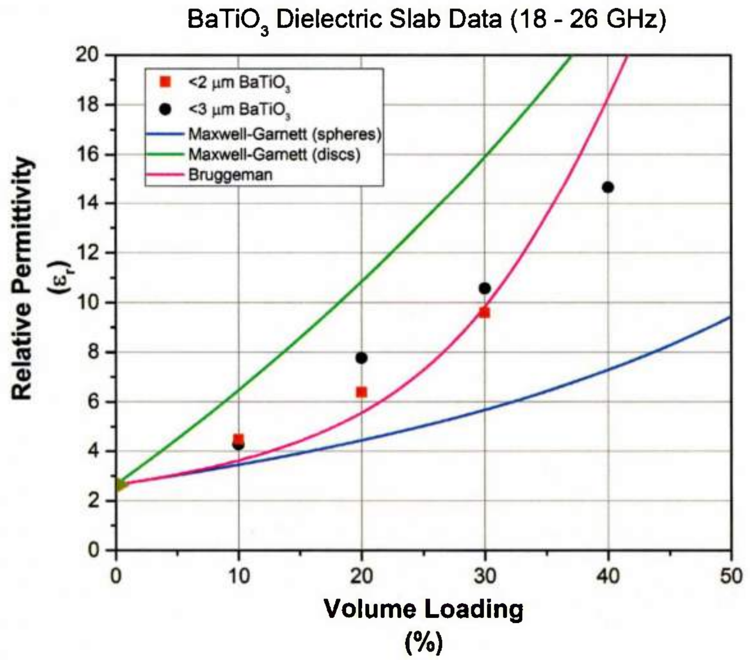


Figure 10. Measured dielectric constant of printed high dielectric samples as a function of BaTiO$_3$ loading. Results for two different BaTiO$_3$ particle sizes are shown. Also shown are fitted curves from three different effective media models.

Table #1

Sample	μ_r	$\tan\delta_m$	ε_r	$\tan\delta_e$
BaTiO$_3$/EPON (10% vol.)	1.0	0	4.3	0.02
BaTiO$_3$/EPON (20% vol.)	1.0	0	6.2	0.09
BaTiO$_3$/EPON (30% vol.)	1.0	0	9.6	0.05
BaTiO$_3$/EPON (40% vol.)	1.0	0	14.3	0.02

B. Results on Additive Manufacturing of High Dielectric Constant Composites

Using the custom magnetic inks described earlier we fabricated a number of plates of various % loading to calibrate the process. The samples were measured at 1 GHz using an Agilent Magnetic Test Fixture. Figure 11. and Table #2 present the results from those measurements.

We could achieve relative permeability as high as μ_r=2.5 at 30% volume loading. The magnetic loss tangent, however, is a bit high ($\tan\delta_m$=0.12). We are currently working on a new synthesis methodology to reduce those losses.

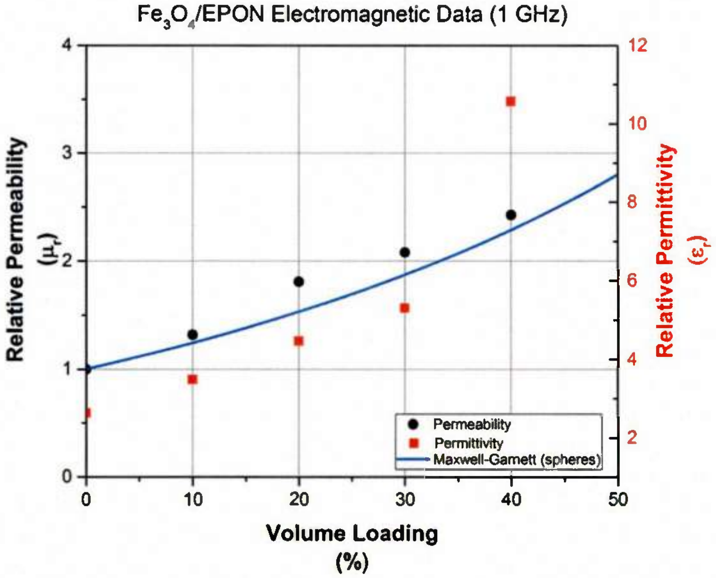


Figure 11. Measured relative permeability and permittivity of printed samples using magnetic inks as a function of Fe_3O_4 loading.

Table #2

Sample	μ_r	$\tan\delta_m$	ε_r	$\tan\delta_e$
Fe_3O_4/EPON (10% vol.)	1.3	0.08	3.1	0.001
Fe_3O_4/EPON (20% vol.)	1.8	0.11	3.8	0.08
Fe_3O_4/EPON (30% vol.)	2.1	0.12	4.6	0.09
Fe_3O_4/EPON (40% vol.)	2.4	0.13	6.2	0.11
$Ni_{0.5}Zn_{0.5}Fe_2O_4$/EPON (20% vol.)	1.9	0.10	3.5	0.10
$Ni_{0.5}Zn_{0.5}Fe_2O_4$/EPON (30% vol.)	2.5	0.12	3.8	0.15

C. Results on Additive Manufacturing of Resistive Composites

The majority of the effort in this project was devoted towards developing a reliable process for fabricating resistive composite fabrics for the application of radar absorbing structures (RAS).

1. Results of Micro-Dispesning of Resistive Inks on Kapton (calibration step)

To determine the precise electromagnetic properties of the DuPont resistive ink (described earlier) we used the nScrypt system to micro-dispense precise volumes of ink on a thin Kapton substrate. A number of samples were printed with increasing volume fraction of ink. The dielectric properties of these samples were measured from 4 GHz – 40 GHz using a free-space measurement system. The results were then used to back out the frequency dependent complex permittivity of the ink. We found that the ink's properties followed a Debye dispersion model as given below:

$$\varepsilon_{ink} = \varepsilon_\infty + \frac{\varepsilon_d}{1+2\pi f\tau} \tag{1}$$

Where the constants in Equation (1) are given in Table #3.

Table #3

	ε_∞	ε_d	τ
Debye Model for DuPont Ink	7.85	2.59	3 * 10^{-8}

2. Results of Screen Printing of Resistive Inks on S-glass Woven Fabric

After determining the precise properties of the Dupont Ink we then used screen printing to print different fill-fractions of ink on woven glass fabrics. We achieved different fill fractions by the geometrical configuration of the screens. Specifically, we printed an array of resistive patches spaced 4.0 mm apart. By varying the size of the patch relative to the patch spacing we can achieve various from 0% (no ink) to 100% (4 mm resistive patches). Figure 12 illustrates four different print patterns.

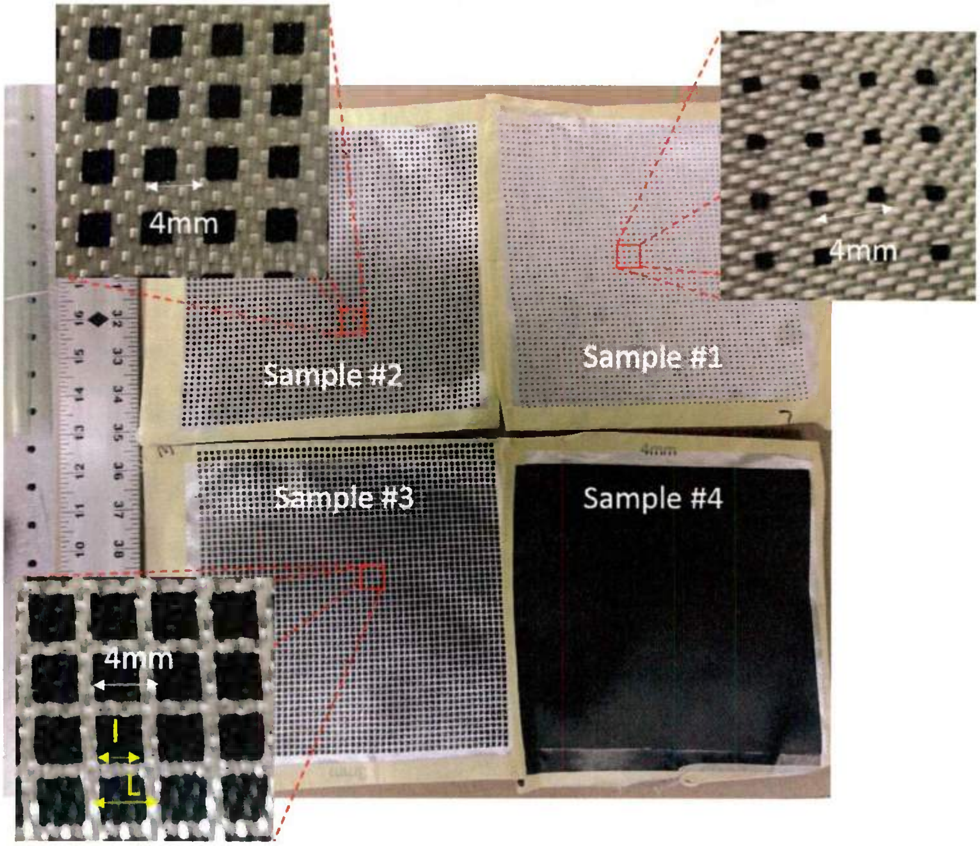


Figure 12. Illustration of screen printed resistive ink patterns on S-glass fabrics.

We fabricated and characterized seven different screen printed patterns using this process. The specifics of those patterns are given in Table #4.

Table #4. Samples of resistive ink screen printed on S-glass fabric.

	Length, l	Period, L	% Ink (weight)
Sample #1	0.5 mm	4.0 mm	0.8%
Sample #2	1.0 mm	4.0 mm	1.1%
Sample #3	1.5 mm	4.0 mm	2.5%
Sample #4	2.0 mm	4.0 mm	3.8%
Sample #5	2.5 mm	4.0 mm	5.1%
Sample #6	3.0 mm	4.0 mm	7.2%
Sample #7	3.5 mm	4.0 mm	9.8%
Sample #8	4.0 mm	4.0 mm	12.5%

Each of these samples were measured over the 4-40 GHz band and the effective permittivity was back out of those measurements. Figure 13 shows the results.

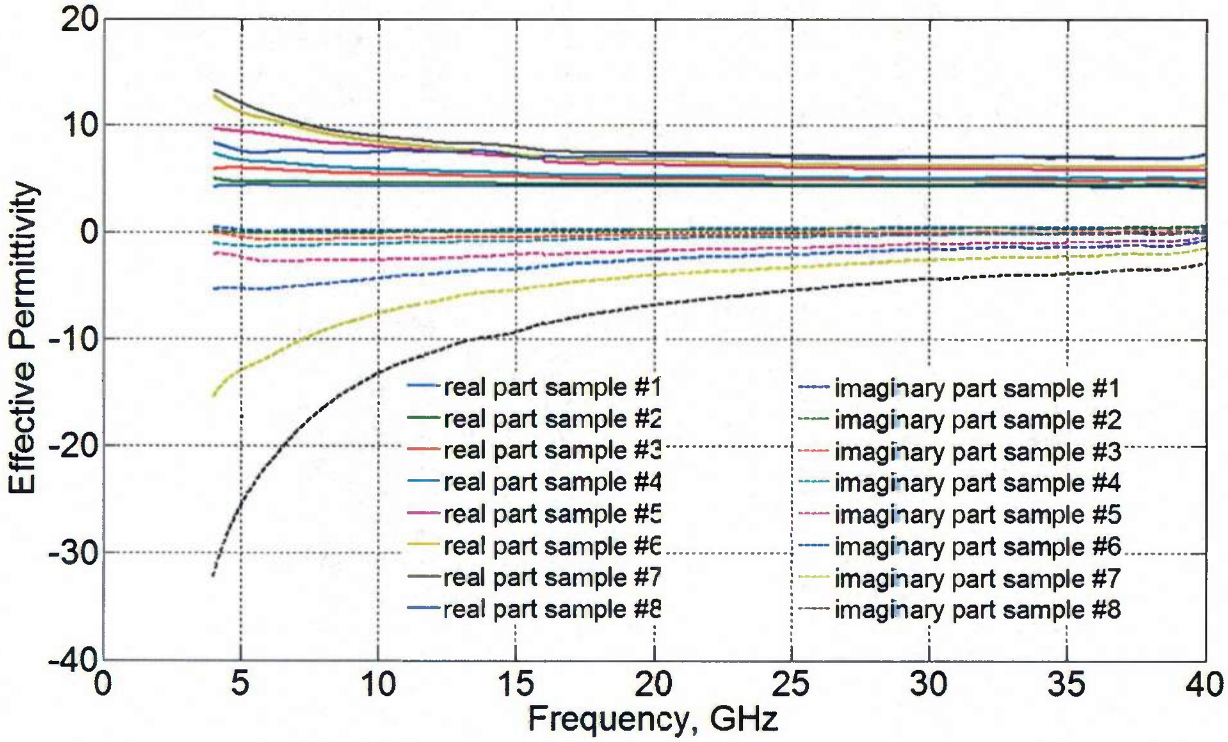


Figure 13. Effective permittivity of the eight printed samples (given in Table 3) of the resistive ink screen printed on S-glass fabric.

The results shown in Figure 13 clearly demonstrate how the RF loss of the fabrics can be prescribed by varying the amount of resistive ink per unit area (i.e. print pattern). Moreover, we can use the Debye model, Equation 2, to predict the properties of the fabrics as shown in Figure 14.

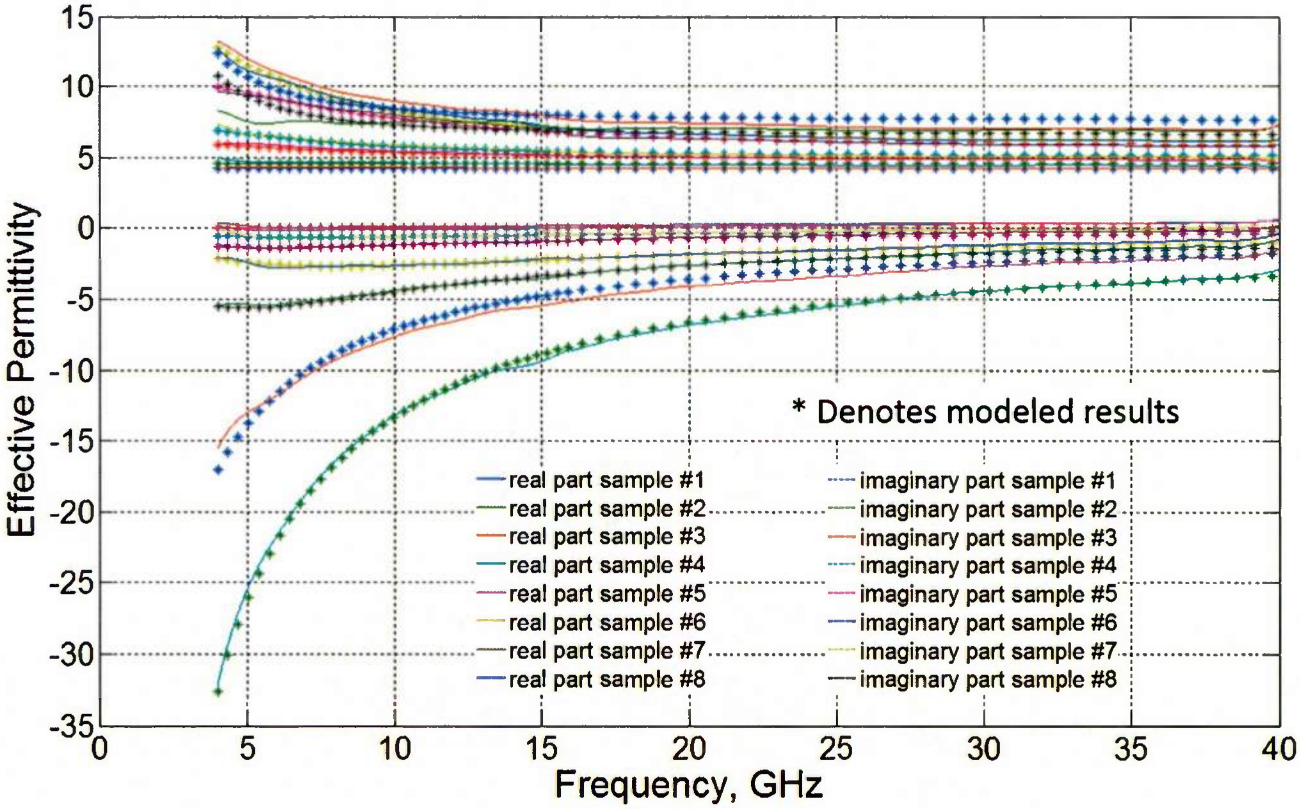
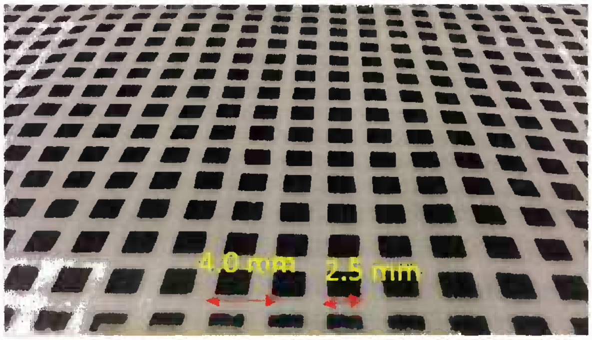


Figure 14. Effective permittivity of the eight printed samples (given in Table 3) of the resistive ink screen printed on S-glass fabric compared to predicted results using a Debye model.

3. Results of Screen Printing of Resistive Inks on Spectra Shield

For applications in radar absorbing armor it would be advantageous to be able to modify the EM properties of materials such as Dyneema or Spectra Shield. To this end, we completed an effort to use screen printing of resistive inks on Honeywell Spectra Shield 2 SR-3124. Similar to the case of woven glass fabrics we printed a number of samples with increasing amounts of resistive inks. Two illustrative samples are shown in Figure 15. Table #5 provides a list of the six different samples that were fabricated.

Sample #1: Ink on Spectra



Sample #2: Ink on Spectra

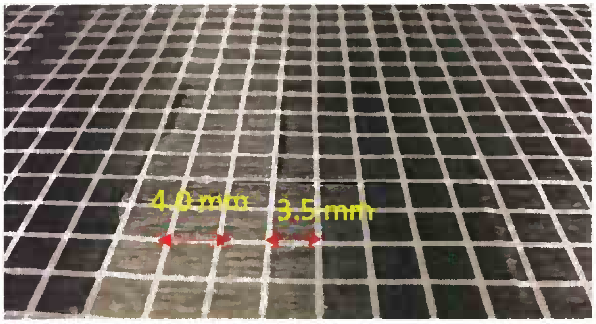


Figure 15. Illustrative examples of resistive inks screen printed on Spectra Shield.

Table #5 Resistive ink printed on Spectra Shield

	Length, l	Period, L	Number of printed layers	% Ink (weight)
Sample #1	1.0 mm	4.0 mm	12	0.00146
Sample #2	2.0 mm	4.0 mm	12	0.00238
Sample #3	2.5 mm	4.0 mm	12	0.00197
Sample #4	3.0 mm	4.0 mm	12	0.00433
Sample #5	3.5 mm	4.0 mm	12	0.00358
Sample #6	4.0 mm	4.0 mm	12	0.00821

The measured results from the samples described in Table #4 are shown in Figure 16 along with the predicted results based on the Debye model.

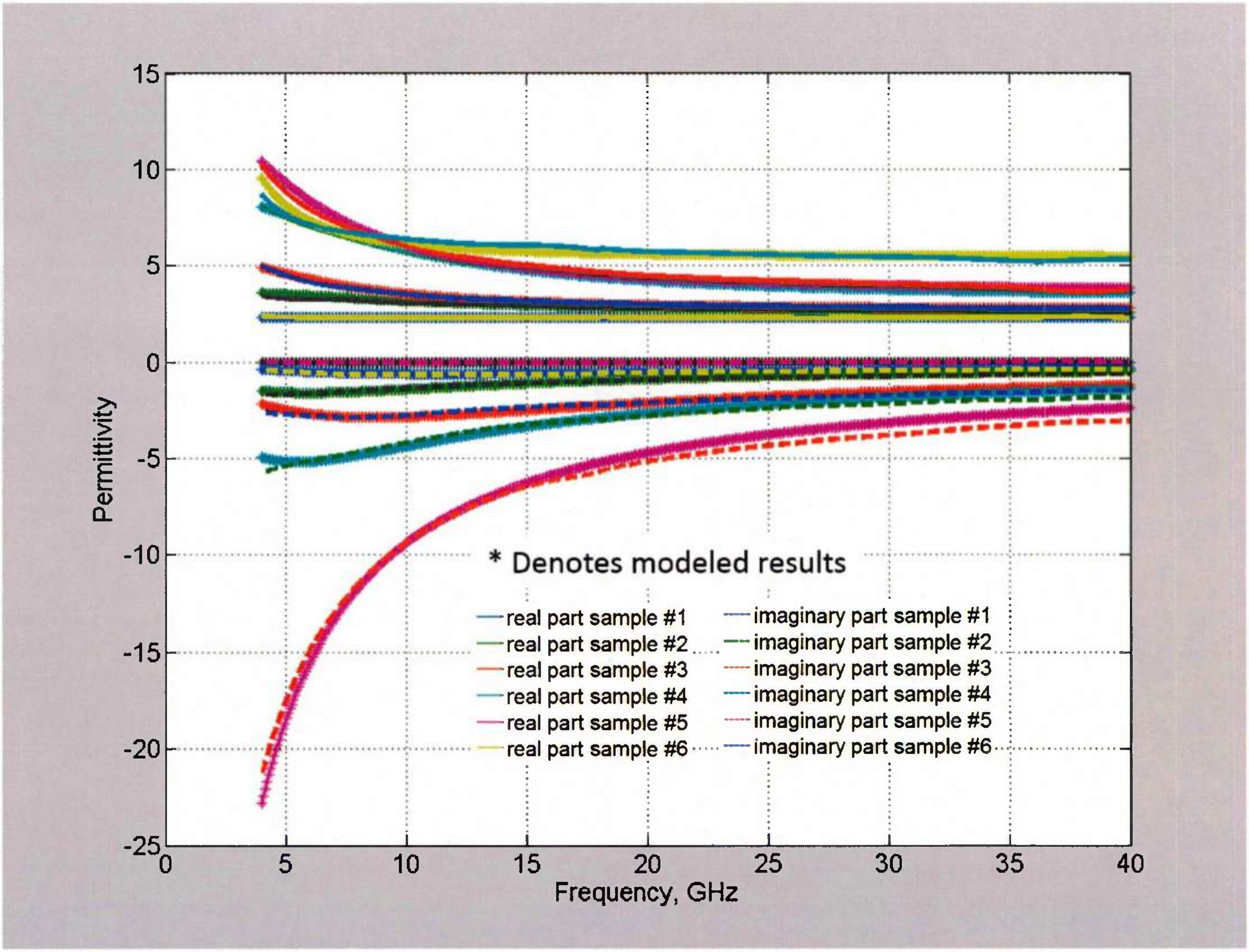


Figure 16. Effective permittivity of the eight printed samples (given in Table 3) of the resistive ink screen printed on Spectra Shield compared to predicted results using a Debye model.

6.0 Summary of Major Accomplishments

In this effort we investigated the use of additive manufacturing to alter the electromagnetic properties of composites. The focus was on creating RF losses in structural composites but we also developed new methods to integrate high permittivity and permeability properties.

The major accomplishments of this effort were:

- We developed a synthesis method for creating high dielectric constant inks/pastes that are well suited for screen printing and micro-dispensing. We validated those properties experimentally.

- We developed a synthesis method for creating magnetic inks/pastes that are well suited for screen printing and micro-dispensing. This included processes for synthesizing the magnetic nanoparticles. We validated those properties experimentally.
- We developed a scalable and cost effective methodology for creating structural woven fabrics with prescribed RF loss properties by screen printing patterns of resistive inks. These materials would then form the backbone of a new method for making radar absorbing structures.
- We developed a scalable and cost effective methodology for creating armored materials (i.e. high molecular weight polyethylene or Spectra Shield) with prescribed RF loss properties by screen printing patterns of resistive inks.
- We derived a Debye based effective media model that closely matches experimental results.
- We worked closely with our partners at the Naval Surface Warfare Center, Carderock Division, to transition these new materials to practical applications of interest to the Navy.

7.0 Publications Resulting from Project

1. P. Pa, Z. Larimore, P. Parsons and **M.S. Mirotznik**, 'Multi-material additive manufacturing of embedded low-profile antennas', **IEEE Electronics Letters**, Vol. 15, No. 20, October 2015
2. B. Good, D. Roper, S. Simmons and **M.S. Mirotznik**, "Design and Fabrication of Microwave Flat Lenses using a Novel Dry Powder Dot Deposition System", **IOP Smart Materials and Structures**, No. 24, October 2015
3. B. Good, S. Simmons and **M.S. Mirotznik**, "Design of Anti-reflection Grading using Magneto-dielectric Materials", **IEEE Transactions on Antennas and Propagation**, Vol. 63, No. 11, November 2015
4. P. Ransom, Z. Larimore, S. Jensen and **M.S. Mirotznik**, "Fabrication of Wideband Antireflective Coatings using Fused Deposition Modeling", summited to **IEEE Electronics Letters**, October 2015.
5. **M.S. Mirotznik**, B. Good, S. Stoyanov and D. Roper, 'Fabrication of Inhomogeneous Magneto-Dielectric Substrates by Functional Additive Manufacturing', **IEEE International Symposium on Antennas and Propagation**, Memphis TN, 2014
6. Z. Larimore, P. Pa, M. Keefe and **M.S. Mirotznik**, 'Additive Manufacturing of Graded Index Flat Lenses via Multi-Material Micro-Dispensing', **IEEE International Symposium on Antennas and Propagation**, Memphis TN, 2014
7. P. Pa, M. Mills, Z. Larimore, S. Yarlagadda and **M.S. Mirotznik**, 'Graded Surface Wave Absorbers Fabricates using Resistive Screen Printing', **IEEE International Symposium on Antennas and Propagation**, Memphis TN, 2014
8. **M.S. Mirotznik**, S. Yarlagadda and L. Kolak, "Ultra-wideband Ballistic Radome with Solid Dyneema® Core," **IEEE International Symposium on Antennas and Propagation**, Vancouver Canada, 2015
9. M. Mills, Z. Larimore, P. Parsons, P. Pa and **M.S. Mirotznik**, 'Synthesizing Artificial Electromagnetic Properties Utilizing Additive Manufacturing', **IEEE International Symposium on Antennas and Propagation**, Vancouver Canada, 2015
10. A. Good, D. Roper and **M.S. Mirotznik**, 'In-plane Characterization of Graded Dielectrics Fabricated Through Additive Manufacturing', **IEEE International Symposium on Antennas and Propagation**, Vancouver Canada, 2015
11. P. Pa, A. Good, Z. Larimore, M. Mills, S. Yarlagadda, **M.S. Mirotznik**, 'Functional Additive Manufacture of Low Profile Antennas Embedded Within a Structural Composite', **RAPID** May 2015

8.0 Graduate Students Supported Through this Effort

1. Dr. Peter Pa – Ph.D in Electrical Engineering, November 2015
2. Mr. Matt Mills – MS in Electrical Engineering, December 2015
3. Mr. Austin Good – MS in Electrical Engineering, Expected May 2016
4. Mr. Zach Larimore – Ph.D. in Electrical Engineering, Expected May 2017
5. Mr. Paul Parson – Ph.D. in Material Science Engineering, Expected May 2017