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3-D Printed Electro-Magnetic Objects for THz Communications

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Chemical Sciences Division

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1. Abstract

Advanced materials and manufacturing techniques will pave the path towards high quality electro-magnetic circuits that operate up through THz and into optics regime. Digital additive manufacturing (AM) techniques offer game-changing potential for large scale manufacturing of Radio-frequency (RF) circuits and system in custom 2D/3D geometries. The technical collaboration will explore the design flexibility and product customization capabilities of additive manufacturing techniques to process magnetic materials in custom 3D geometries with tailored dielectric properties and frequency response characteristics. Transformation of an RF circuit design idea into a 3D printed system using additive manufacturing techniques will bring together the elements of advanced materials, additive integration, and low-cost manufacturing for future advanced wireless communication systems.

2. Statement of Objectives

The objectives of the work are as follows:

1. 3D printed RF circuit design with port loss of 1 dB and return loss of 15-18 dB at the center frequency of operation
2. Select magnetic powder feedstock with the target composition and particle size suitable for 3D printing
3. Develop Binder Jet process to meet RF component design specifications
4. Correlate RF characteristics with the material composition, and 3D printing and post-processing parameters

3. Benefits to the Funding DOE Office's Mission

Binder jet additive manufacturing is a low-cost method for producing parts with enhanced geometries that are less energy intensive to manufacturing and potentially reduce energy usage of the machine they are integrated into (due to light weighting, enhanced heat transfer, etc.). For communications, the opportunity exists to improve the efficiency of RF magnetic circuits. The process parameter development proposed in this work is critical for enabling the use of additive manufacturing technologies like binder jetting as manufacturing industries typically don't have the know-how to do this work themselves. Overall, the advancement of the utilization of the additive techniques could lead to the adoption of additive manufacturing technology by magnet manufacturing companies, and lead to job growth and higher US global manufacturing competitiveness.

4. Technical Discussion of Work Performed by All Parties

Three main tasks were proposed as the structure of this CRADA, which are:

1. RF Object Design (Harris): Design a circulator operating in the range of 10 to 20 GHz
2. Material Exploration (ORNL & Harris): Select Fe-Si alloy composition for RF circuit
3. Printing and Fabrication (ORNL): Develop AM process for 3D printing of RF component
4. Laboratory Testing: Correlate RF characteristics with the material composition, and 3D printing and post-processing parameters

A summary of each task is as follows:

Task 1: Design a circulator operating in the range of 10 to 20 GHz

Harris corporation designed a circulator operating in the range of 10 to 20 GHz. This design was developed based on their previous successful demonstration of the 60 GHz applications. They explored the potential of 3-D printing technologies for the development of free space quasioptical (Q-O) components operating in the millimeter wave frequency regime. Q-O techniques are used to focus millimeter wave signals for power combining applications. This study includes the design process, simulation, fabrication, and testing of dual biconvex shaped lens systems designed for 60 GHz center frequencies (as shown in Figure 1) [1]. Test results demonstrate the resultant gain across a 15- wavelength gap between the input and output waveguides in comparison to free space coupling between the two. This study presents a set of unique designs that includes separated lens and alignments structures to facilitate efficient high-resolution lens printing. The 60 GHz system features lenses placed in a self-aligning cavity. The resulting data showed a focusing gain of 18.3 dB at 60 GHz and a gain of 22.1 dB at 100 GHz. The system shown in Figure 1 will be modified to 10 to 20 GHz range applications

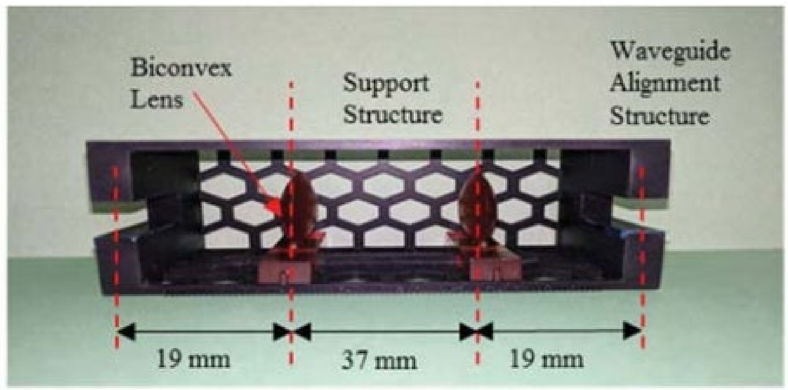

Figure 1. 3-D printed lens system with 60 GHz design.

Task 2: Select Fe-Si alloy composition for RF circuit

Soft magnetic silicon (Si) steel with 3 wt.% Si (Fe3Si) is widely used in electrical applications such as transformers, magnetic shielding, motor stators, and generators where high magnetic permeability and low loss Fe-based materials are required. However, higher amounts of Si for example 6.5 wt.% Si (Fe6Si) in steel increase the electrical resistance of the material and further improve the magnetic properties. Based on the magnetic properties, Fe6Si composition was selected for further study. The spherical shaped Fe6Si starting powders were purchased from Carpenter for this study. The microstructure and particle size distribution of Fe6Si powders is shown in Figure 2.

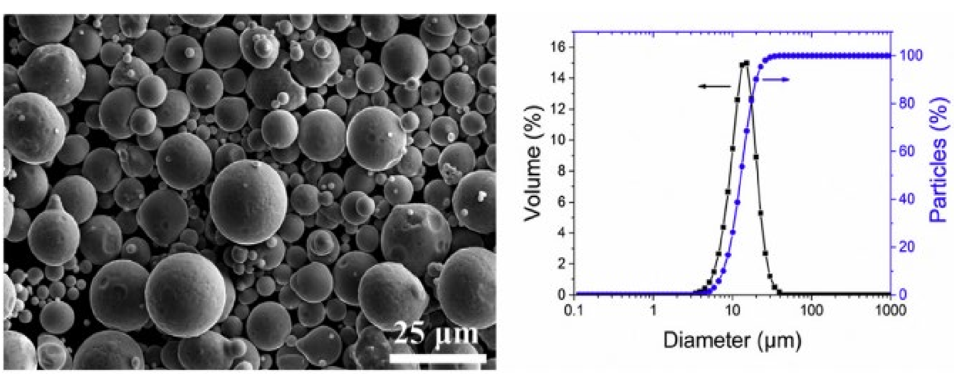

Figure 2. Scanning electron microscopy image of Fe6Si powders (left) and the Horiba volume distribution and particle percentage data (right) [2].

Task 3: Develop AM process for 3D printing of RF component

Binderjet additive method was selected for this study. Binderjet is an AM process that dispenses liquid binding agent on the feedstock powder to form a 2-D pattern of the cross section of the 3-D model on a layer. The layers are then stacked, and the process repeats itself until the whole part is printed. A layer of powder is spread for each layer of the part, with the build platform lowered by one layer height after each layer is made to make room for the next layer. The as-printed parts directly off the printer are usually fragile "green" parts and need postprocessing to improve their mechanical properties. In binderjet process, multimodal powder mixtures (for example Fe6Si pre-mixed with 1-3 wt.% of ceramic powders) have been used to produce composite magnets with improved packing density. The green part obtained is post-sintered at >1200 °C overnight in a high vacuum to achieve full density composite magnets.

Figure 3. Image of binderjet printed Fe6Si soft magnets (Size: 1" cube).

Task 4: Correlate RF characteristics with the material composition, and 3D printing and post-processing parameters

We have successfully 3-D printed Fe6Si samples with and without 1 wt.% of ceramic powders using the binderjet process. The material properties of these samples are shown in Table 1. Based on the properties of these composite magnets, further optimization is needed for RF studies.

Table 1: Material properties of the 3-D printed Fe6Si samples.

Samples	Max relative permeability	Theoretical density (g/cc)	Measured density (g/cc)	Resistivity at 300K (μΩ·cm)	Saturation magnetization at 3T field (T)
Fe6Si	6.15	7.34	6.87	93	1.44
Fe6Si-1 wt.% ceramic powder	9.75	7.3	6.84	70	1.34

5. Subject Inventions (As defined in the CRADA)

The following invention disclosures were filed:

- Inventions: None

6. Commercialization Possibilities

Harris Corporation offers a better option for Radio-frequency (RF) circuits and system in custom 2D/3D geometries. Here we demonstrated a binderjet process to fabricate Fe6Si magnets with and without ceramic additives. Further improvements are necessary with optimized additives.

7. Plans for Future Collaboration

Additive manufacturing offers significant advantages such as cost effectiveness (no tooling required), fast speed, and capability of producing parts of unlimited in sizes and shapes. Therefore, binderjet process provides an effective method in realizing arbitrary shape with minimum cost and waste, and has the potential to revolutionize large-scale industry production of composite magnets. In the future work, the use of printed magnets with optimized doping will be tested for high quality electro-magnetic circuits that operate up through THz and into optics regime.

8. Conclusions

In this work, we report the feasibility of using binderjet process to print soft composite magnets with complex shapes and sizes. Preliminary results on the magnet fabrication with Fe6Si magnet powders are promising. Further process optimization is necessary to improve the magnetic and dielectric properties.

9. Selected Publications/References:

Publications: None

References:

[1] C. D. Fisher, A. C. Paolella, C. Corey, D. Foster, and D. Silva-Saez, "3-D Printed Millimeter Wave Quasi-Optical Lens System for 60 and 100 GHz Applications," 2019 Wireless and Radio Systems Symposium (WRS), IEEE Xplore, p. 174 (2019).

[2] C. L. Cramer, *et al.* Binder jet additive manufacturing method to fabricate near net shape crack-free highly dense Fe-6.5 wt.% Si soft magnets. Heliyon **5**, (2019).