The Design of Radiofrequency (RF) Structures in Additive Manufacturing

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Design of Radio Frequency Systems and Sensors for Multi-Material Additive Manufacturing

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Outline

Design of Radio Frequency Systems and Sensors for Multi-Material Additive Manufacturing

- Brief overview of what we are trying to do and why
- Discuss some of the major design challenges we face in this application area
- Provide a more detailed illustrative example
Our Goal

End-to-End AM Design and Fabrication of High Frequency Electronic Systems

Antennas

Integration of passive and active integrated circuits —

Connectors

Transmission lines
Application Space

Small Volume – Labor Intensive Parts or Systems

https://www.nature.com/articles/s41598-017-01276-4
Application Space

Parts that Cannot be Produced Through Other Means

Examples

- Spatially graded material properties
- Complex 3D geometries
- Conformal devices
Managing Expectations

What Most People Want

What Most People End Up With

The state of the art is somewhere in between


http://papaya3dp.com/?r=app&s=18
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Design Considerations for AM of High Frequency Electronic Systems

While still important structural properties are not as important as other design considerations for our applications ...

Such as:

- Ability to print considerably different materials without registration errors (i.e. single multimaterial printer is ideal)
- Materials with electric and magnetic properties that can match standard technologies (e.g. lithographic methods).
- Materials that handle potentially large temperature gradients (e.g. microprocessors and amplifiers get hot!) or design and implement thermal management solutions.
- Ability to place and electrically bond chip level integrated circuits (we still can’t print these)
- Ability to print at vastly different length scales (i.e. size matters a lot!).
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Primary Multimaterial AM System

- Quad deposition heads
- Material Agnostic via micro-dispensing print heads
- Prints viscosities from 1-1 million cp
- Volumetric dispense control down to 100 picoliters
- Line sizes ~25-500 μm
- Ability to print on conformal surfaces via integrated laser scanning
- Ability to print thermoplastics (FDM)
- Positional control down to 1μm
- Pick and place of active circuit components
Primary Multimaterial AM System
Material Challenges

- Finding suitable materials is one of the biggest challenges in moving this technology forward.

- For high frequency applications (>10 GHz) some of the challenges in AM compatible materials

  1. Electrical conductivities <10% of bulk metal properties.
  2. High temperature low-loss polymer substrates that can withstand soldering.
  3. High dielectric constant and magnetic materials.
  4. Long list of printable active materials: (a) temperature sensitive, (b) chemically sensing, (c) electrochromic, (d) phase changing, (d) fluorescent, (e) photovoltaic, .....
Material Development

Resistive Inks

- Carbon black powder
- Carbon nanotubes
- Polymer matrix

- Attractive EM loss properties
- Nice viscosity for AM printing
- Low cost
- No volatiles

Metallic Inks

- Silver flakes + Silver nano-particles
- No organic binder
- Potential for near bulk metallic properties
- Been used for printable RF transmission lines and antennas
- Adjustable viscosities
Material Development

Active Phase Changing Inks

Vanadium oxide (VO$_2$)

Resistivity (Ohms)

Time (seconds)

Under ambient light
The printed array of squares is largely transparent.

Under UV light illumination
The array of printed squares are fluorescent.

- Quantum dots + hydrophilic resin
- Design inks that adhere to a wide range of surfaces: Clothing/Fabrics, Leather, Metal, Plastics
- Potential use for anti-tampering applications.

Fluorescent Inks
Material Development

Chemiresistive Inks

![Images of chemiresistive inks and graph showing resistance over time for different gases.]
Material Development

Material Development: Custom Polymer Filaments

- Polymer powder
- Additives

Custom filaments

- Print using FDM

ThermoFisher Process 11 Twin Screw Polymer Extruder
Material Development

Material Development: Custom Polymer Filaments
Low Dielectric Constant Filaments ($\varepsilon_r < 2.0$)

Hollow glass microspheres within a Polyethylene Matrix

Hollow Glass Microspheres
within a Polyethylene Matrix

Relative Permittivity ($\varepsilon_r$)

Volume loading Hollow Glass Spheres (%)
Material Development: Hopper Fed System for Highly Loaded Materials

Diagram showing the components of the hopper fed system:
- Hopper for feeding powder mixtures
- Stepper motor
- Powder feeding mechanism
- Single screw extruder
- Extrusion barrel
- Cartridge heaters
- Nozzle heater
- nScrypt ceramic nozzle tips

Version 1.0
Process Monitoring and Control

- Most AM systems, including our nScrypt systems, are entirely open loop.

- There is a critical need for process monitoring and control features.

Our FDM head some Monday morning ....
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Applications

Printed Antennas

Printed Sensors

Printed Pharmaceuticals

Spatially Graded Beam Formers

Printed High Frequency Electronics
Applications

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Spatially Graded Beam Formers
Goal

Fabricate complex 3D geometries in which the electrical properties (e.g. dielectric constant) vary nearly arbitrarily in three dimensions

$$\varepsilon(x, y, z)$$
Illustrative Example: 3D Printed Graded Dielectrics

Application: Electronic Beam Steering

Radar Systems

Satellite Communications

5G Wireless Communications
Illustrative Example: 3D Printed Graded Dielectrics

Application: Electronic Beam Steering

Phased array technology
- All electronics
- Very flexible
- Narrow bandwidths
- Very expensive

Mechanically steered antenna
- Simple
- Heavy
- Large
- Susceptible to mechanical breakdowns
Illustrative Example:
3D Printed Graded Dielectrics

Another Approach: Passive Beam Steering using Luneburg Lens

\[
\epsilon(r) = 2 - \left(\frac{r}{R}\right)^2
\]
Illustrative Example: 3D Printed Graded Dielectrics

Application: Electronic Beam Steering
Another Approach: Passive Beam Steering

- Wide bandwidths
- Inexpensive materials
- Simultaneous multi-beams
- Relatively small and lightweight
- Hard to fabricate!
We explored approaches for designing and fabricating spatially graded structures in 3D using FDM.

- Many FDM polymers have very low material losses at high frequencies.
- FDM systems are extremely common and inexpensive.

$$\varepsilon(x, y, z)$$
How do we create graded properties?: Space Filling Curves

Illustrative Example:
3D Printed Graded Dielectrics

How do we create graded properties?: Space Filling Curves

Illustrative Example:
3D Printed Graded Dielectrics

Micro-CT scan of printed space filling curve

$A_{cross} = h(W - h) + \pi \left(\frac{h}{2}\right)^2$

$\Lambda$ $\Lambda$

$VF = \frac{A_{cross} \cdot L_{tot}}{\Lambda^2 \cdot h}$

$\Lambda$ $\Lambda$

$VF = \frac{\left(W - \left(1 - \frac{\pi}{4}\right)h\right) \cdot (N + 1)}{\Lambda}$

Volume fraction of printed material per unit cell
Illustrative Example:
3D Printed Graded Dielectrics

Material: Polycarbonate
Illustrative Example:
3D Printed Graded Dielectrics

Use of Space Filling Curves: Design process
Illustrative Example:
3D Printed Graded Dielectrics

Use of Space Filling Curves: Design process

2 mm
Illustrative Example:
3D Printed Graded Dielectrics

Luneburg Lens Beam Steering

Fabricated Luneburg Lens using 3D Printing

- 8-18 GHz
- 26-40 GHz
- 60-110 GHz
Illustrative Example:
3D Printed Graded Dielectrics

Luneburg Lens Beam Steering at 70 - 110 GHz
Illustrative Example:
3D Printed Graded Dielectrics

Luneburg Lens Beam Steering at 24 GHz

» Receiver: Luneburg lens focuses incoming signal into power detector via bowtie antenna
» Current receiver: only 3 feed antennas. Will scale up in next version
» Lens size: 64 mm diameter
Illustrative Example:
3D Printed Graded Dielectrics

Luneburg Lens Beam Steering

- 24.15 GHZ Source
- Luneburg Lens System
- Rotational Stage
Illustrative Example:
3D Printed Graded Dielectrics

Luneburg Lens Beam Steering

Screen Capture of Android Device

Testing Platform in Action
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