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Fused deposition modelling for microwave circuits & antennas

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Abstract - **Additive Manufacturing, or 3D printing, is moving from the research labs and into both consumer and commercial manufacturing markets. As the systems, processes and materials available are becoming more mature we are seeing them being tested for new application areas such as electronics. In this paper we review how fused deposition modelling (FDM) is being explored for creating microwave circuits and componentry, their RF performance and the materials challenges faced. In recent years such microwave circuits and components have included antennas, lenses, anti-reflective coatings, transmission lines and planar circuits, waveguide terminations, performing at frequencies ranging from low GHz up to tens of GHz. Additive manufacture of such objects allows new, novel and complex structures to be fabricated with lower impact on the environment relative to current manufacturing processes, plus the rapid prototyping of circuits. Additionally it currently offers reasonable RF performance that can be competitive through further advances in manufacturing processes and materials.**

Index Terms — **Fused deposition modelling, microwave, manufacturing, materials.**

1. Introduction

Over the past 2 years the additive manufacturing process Fused Deposition Modelling (FDM) has been used as a platform for investigating the potential for microwave circuits and componentry. FDM is a manufacturing technique that is becoming increasingly common with the growing range of desktop units available from companies such as Ultimaker®, Makerbot® and nScrypt®. Typically structures are designed digitally, then the files are processed with software whereby the design is sliced into layers. These layers are then physically deposited by the FDM unit using thermoplastic polymers. The broadening of the range of polymers and materials deployed in FDM are being investigated by several research groups and, within the papers reviewed, the microwave characterization of these materials after FDM processing can be seen as a further way to opening up the use of FDM as a manufacturing option for microwave circuits and components.

2. FDM Di-electrics

As identified by Deffenbaugh, Rumf & Church [1], microwave frequency characterization of 3D printable materials is essential for the design and manufacture of microwave circuitry, which their paper aimed to address. Three materials suitable for FDM were assessed over the frequency range 0.1 – 11 GHz; polycarbonate (PC), acrylonitrile butadiene styrene (ABS) and a PC-ABS blend. For each material, three measurement methods were used and assessed for their accuracy:

- I-V capacitance (0.1 – 0.2 GHz)
- Radio frequency current-voltage (0.1 – 1 GHz), &,
- Nicholson Ross Weir (8.2 – 11 GHz)

Results from these measurements have been used to support the design of planar circuits over the frequency range 0.5 – 15 GHz [2]-[6] using ABS and PC where presented in Table I the following values have been given for ε_r and tan δ:

TABLE I
Dielectric properties of FDM materials

Material	ε_r	tan δ
PC for antenna substrate up to 2 GHz [2]	2.95	0.01
ABS for co-planar waveguide up to 6 GHz [3]	2.37	0.0037
PC for antenna @ 2.45 GHz [4]	2.89	0.0066
ABS stripline: 0.5 – 15 GHz [5]	2.6	0.007
ABS phased antenna array unit @ 2.45 GHz [6]	2.6	0.007

Furthermore, Zhang, Njoku, Whittow & Vardaxoglou have produced separately a microwave substrate [7] and a lens [8] using FDM. In the former, PLA is assessed as a dielectric substrate whereby the substrate structure is adapted through the FDM process to produce varying dielectric constants. At 2.4GHz, manufactured substrates were produced in solid PLA displaying $\varepsilon_r = 2.72$ and tan $\delta = 0.008$, and various volume fractions (VF) with at 18% VF, $\varepsilon_r = 1.24$ and tan $\delta = 0.002$. Dielectric measurements were performed using a split post dielectric resonator. The lens was fabricated with a composite ABS based mixture ($\varepsilon_r = 4.4$) whereby the relative permittivity was varied in concentric circles. This was achieved by decreasing the volume fill fraction of thermoplastic polymer and thereby increasing the air content. The dielectric constant of the ABS composite structure was varied between $\varepsilon_r = 4.4$ for

100% volume fraction for the inner circle, down to $\varepsilon_r = 1.9$ with a 26% volume fraction for the outer circle.

3. Introducing multi-material: conductive pastes and lossy materials

FDM processing has also been used for printing X-band waveguide terminations, using carbon loaded ABS [9]. In this instance, a waveguide load was created and compared to a commercial HP termination. The carbon loaded ABS was assessed to have ε_r between 10.3 and 9.93 over the X-band. The performance of the FDM load was seen to be comparable to the commercially available load, with the former displaying a VSWR lower than 1.025 over the whole X-band.

Printed conductive pastes and inks have been deployed for planar circuitry that contain silver in the form of nanoparticles or flakes [2]–[6]. The conductivity of the inks is dependent upon the curing process. For example, this can be limited by the polymer's tolerances to temperature thereby limiting the curing temperature used to cure the ink or paste that has been deposited on it. Ketterl et al. [6] showed how increasing cure temperature increases the conductivity of the Ag paste, with a maximum DC conductivity of 4.63e6 S/m for a cure temperature of 160°C. However, curing at this temperature then limits the choice of FDM materials that can be deployed to create substrates due to their heat deflection temperature.

4. Manufacturing Challenges

Fused deposition modelling of microwave circuits offers environmental, cost and design benefits, yet there are still significant challenges for it as a manufacturing technique. Multimaterial processing is highly desirable for microwave engineers designing planar circuits. However, the conductivity of the deposited metal is a key requirement to reduce high frequency losses. In moving to multimaterial processing there is also the challenge of optimizing any pre and post processing to ensure the resulting manufactured structure has the designed electromagnetic and mechanical properties. Additionally, the surface roughness of the FDM structure impacts upon the deposition of the conductive tracks, further hindering RF performance when compared to standard processed circuits.

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