Additively manufactured heterogeneous substrates for three-dimensional control of local permittivity

J. Tribe, W.G. Whittow, R.W. Kay and J.C. Vardaxoglou

The concept of using additive manufacturing as a method to construct heterogeneous substrates from a single building material via stereolithography is introduced. The dynamic variation of air cavities within the bulk material is used to control the effective permittivity of the host medium. The digitally driven layer process enables full three-dimensional variation of the local permittivity. The high resolution of stereolithography enables sub-millimetre control of air inclusion features. Measurements of the effective permittivity with different air fractions have been compared to analytical results.

Introduction: The relentlessly increasing demand for wirelessly enabled devices is continuously driving the requirement for more compact antennas without comprising performance. Conventionally antenna designers are restricted by having to use homogenous substrates with specific permittivities and thicknesses. However, by locally changing the permittivity of a host material, the geometry and performance of an antenna can be influenced [1]. Moreover, areas such as transformation optics will also benefit from the methods in which graded permittivity can be generated within the dielectric material. One method for controlling the permittivity is through the use of small ($\ll\lambda$)inclusions within a host dielectric. The effective permittivity of the mixture is dependent on the properties of the host and inclusions as well as the size and spacing of these inclusions [2]. Analytical values of the effective permittivity with small repetitive air cavities can be calculated using the following equation [3]:

$$k = k_1\left(1 - \frac{3f}{(2k_1+1)/(k_1-1)+f}\right) \qquad (1)$$

where k is the effective permittivity of the mixture, k_1 is the permittivity of the dielectric host material and f is the volume fraction of air.

Additive manufacturing commonly referred to as three-dimensional (3D) printing is a range of processes that create parts layer-by-layer directly from computer-aided design (CAD) data. Additive manufacturing allows the generation of complex geometries and mass customisable parts. Stereolithography uses photons typically produced from an ultraviolet laser to selectively cure a liquid photopolymer in a vat through light-activated polymerisation. This process has the capability of creating highly intricate 3D structures with repeatability and reliability at resolutions below 100 µm [4]. Additive manufacturing can also be advantageous in terms of resource efficiency compared with conventional template-driven production techniques such as lithography or etching where excess material is removed during or after processing [5].

In this Letter, the fabrication of these bespoke and heterogeneous materials has been demonstrated using stereolithography. This was achieved by varying either the air cavity size or spacing within the host medium to create a range of volume fractions and hence effective permittivity values. This approach therefore enables the substrate's dielectric properties to be graded across the material in three dimensions using just one building material.

Design rules for air inclusions: A test matrix was generated to look at the minimum possible air inclusion sizes that could be fabricated using a Viper Si^2 stereolithography system with a photoacid-cured epoxy resin material with a 355 nm spectral sensitive peak. As the stereolithography process uses a liquid resin, drain holes are required to ensure that uncured resin does not get trapped within the enclosed structures. After manufacture, the parts are raised from the vat so the uncured resin flows away. The parts are then rinsed and immersed in a solvent such as methanol to completely clean the internal and external structures. To test these physical limitations, the CAD design as shown in Fig. 1 was manufactured. This included varying feature sizes from 100to 2000 µm and drain holes from 50 to 500 µm. The features chosen were cubes and spheres, but other shapes can be easily generated directly from the CAD data.

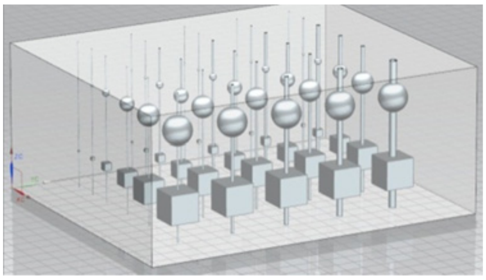

Fig. 1 *3D CAD model to test stereolithography limitations*

The smallest possible feature and drain hole size manufactured and completely cleared of uncured resin were 500 and 150 µm, respectively. As the samples were rinsed and immersed, very small drain holes inhibited the fluid circulation required to clear the uncured resin from the channels and inclusions. Incorporating sonic agitation would increase the effectiveness of clearing smaller drain holes [6]. Micro-stereolithography where optics are used to reduce the spot size of the laser would allow finer feature sizes to be generated; however, the issues of draining the inclusions would still need to be addressed. Methods to remove the drain holes could be achieved by laminating individually produced layers together rather than generating the bulk substrate in a single build.

Samples with air inclusions: After determining the minimum enclosed feature sizes possible with the stereolithography apparatus, 95 × 95 mm substrates were designed and manufactured containing equally spaced air inclusions so the effective permittivity of the mixture could be measured. The inclusions were chosen to be cubes over spheres as higher volume fractions are possible with the same distance between each feature. These samples used 2 mm cubic air cavities with a range of pitch sizes to obtain varying volume fractions and hence different effective permittivities. An example of a fabricated part can be seen in Fig. 2.

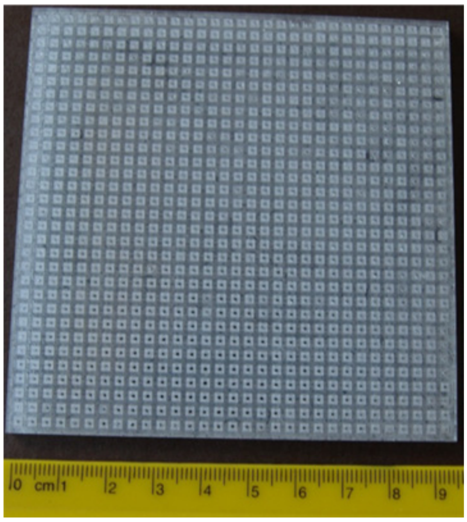

Fig. 2 *Manufactured sample with 2 mm air inclusions and 3 mm spacing*

Measured results: The effective permittivity was measured at 1900 MHz using the split post dielectric resonator technique [7] as shown in Fig. 3. Three samples were measured with 23, 30 and 40% air volume fractions using 2 mm air cubes with regular pitch size in all three dimensions. The results of the measurements along with the analytical permittivity values can be seen in Table 1. Each sample was measured 10 times and an average was calculated. The measured relative permittivity of the solid (0% air) substrate was 3.08. The effective permittivity showed a decrease with increased volume fraction of air in line with the analytical values.

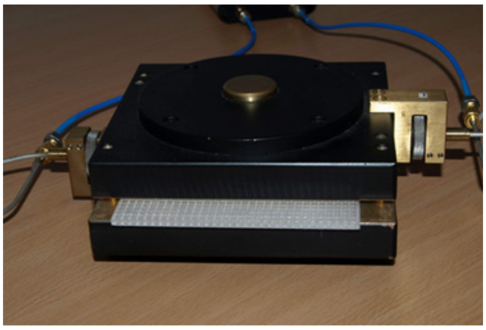

Fig. 3 *Sample in split post dielectric resonator*

Table 1: Measured effective permittivity and analytical values

Pitch in all three dimensions (mm)	Volume fraction of air (%)	Analytical effective relative permittivity from (1)	Measured effective relative permittivity
—	0	3.08	3.08
3.26	23	2.50	2.65
3.0	30	2.33	2.50
2.7	40	2.12	2.32

Conclusion: This Letter has introduced a novel approach to enable local control of the effective permittivity within a substrate via the use of the stereolithography process. The additively manufactured heterogeneous substrates were produced from a single building material containing air cavities in a controlled configuration and geometry. Increasing the volume fraction of air inclusions within a dielectric reduced its effective permittivity. Therefore, a substrate with a locally graded permittivity can be fabricated from one material by varying the air cavity size or pitch. This creates new degrees of freedom for antenna engineers. With this particular stereolithography apparatus, it is possible to create features with a resolution of ˜ 500 µm and with 150 µm diameter drain holes. Further reductions in the feature size and a closer agreement with the analytical theory could be achieved using micro-stereolithography and sonic cleaning to remove the uncured resin from the inclusions. By changing the aspect ratio of the air inclusions, the same process can be used to fabricate anisotropic substrates.

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One or more of the Figures in this Letter are available in colour online.

J. Tribe, W.G. Whittow and J.C. Vardaxoglou (*School of Electronic, Electrical and Systems Engineering, Loughborough University, Loughborough LE11 3TU, United Kingdom*)

E-mail: W.G.Whittow@lboro.ac.uk

R.W. Kay (*Additive Manufacturing Research Group, School of Mechanical and Manufacturing Engineering, Wolfson Building, Loughborough University, Loughborough LE11 3TU, United Kingdom*)

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