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

J. Tribe, W.G. Whitlow, 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.

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 S™ 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 does not get trapped within the enclosed structures. Incorporating sonic agitation would increase the effectiveness of clearing smaller drain holes [8]. 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.

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. 1 3D CAD model to test stereolithography limitations

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

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**Table 1:** Measured effective permittivity and analytical values

<table>
<thead>
<tr>
<th>Pitch in all three dimensions (mm)</th>
<th>Volume fraction of air (%)</th>
<th>Analytical effective relative permittivity from (1)</th>
<th>Measured effective relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>0</td>
<td>3.08</td>
<td>3.08</td>
</tr>
<tr>
<td>3.26</td>
<td>23</td>
<td>2.50</td>
<td>2.65</td>
</tr>
<tr>
<td>3.0</td>
<td>30</td>
<td>2.33</td>
<td>2.50</td>
</tr>
<tr>
<td>2.7</td>
<td>40</td>
<td>2.12</td>
<td>2.32</td>
</tr>
</tbody>
</table>

**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.W. 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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