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3D Printed Substrates with Graded Dielectric Properties and Their Application to Patch Antennas

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Abstract— Effects of using air voids to vary the effective permittivity of Acrylonitrile-Butadiene-Styrene (ABS) TP20280 thermoplastic filament have been investigated. Measurements of the relative permittivity and loss tangent of 3D printed substrates with different infill fractions have been made. A 3D printer has been used to manufacture heterogeneous antenna substrates, allowing for extra degrees of design freedom; specifically, varying the relative permittivity as a function of substrate location. S_{11} magnitude responses and performance parameters of heterogeneous antenna prototypes have been measured and validated through comparison with simulated data. Results presented conclude that patch antenna with linear variation of relative permittivity perpendicular to major current direction improved impedance match of the second resonant frequency, when compared with a traditional homogenous substrate patch antenna.

Keywords—3D printing, heterogeneous substrates, ABS filament

I. INTRODUCTION

Microstrip patch antennas provide low cost, easy to manufacture, directional and lightweight [1] solution to wide range of communication applications in today's world. As technologies evolve, communication engineers are required to develop new methods of controlling antenna behaviour. Recent years have seen an increase in popularity of microstrip antennas in wireless communication. Over past few decades, various papers have been published which concern enhancing patch antenna performance, such as broadening bandwidth [2-4], increasing antenna gain [5-8] and improving total efficiency [9, 10]. In this paper, the dielectric properties of different samples have been measured; different antenna heterogeneous substrates have been investigated via simulations and measurements. The dielectric properties of materials can be measured using a split post dielectric resonator (SPDR) and a microwave frequency Q-meter [11]. Further details about artificial dielectrics can be found in [12-14]. Heterogeneous materials have been used for lenses [15,16].

II. DIELECTRIC MEASUREMENTS OF 3D PRINTED SAMPLES

The effects of varying relative permittivity by creating air voids in ABS material was investigated through manufacture of material samples with a range of infill volume values, starting with 10% and finishing with 100% in increments of 10%. Effect on the loss tangent of the material was also

investigated in the same manner. The sample and the SPDR are shown in Fig. 1.

Fig. 1. 3D printed sample in SPDR

Measurements were conducted at frequencies of 1.9GHz and 2.4GHz to determine the effect of operating frequency on relative permittivity and loss tangent parameters of ABS material. Samples with different infill percentages are shown in Figure 2. The samples were 70mm (w) $\times$ 70mm (l) $\times$ 3mm (h). The sample was created using ten 0.3mm thin layered planes during the printing process. Measurements of each infill volume sample were conducted three times and an average was taken to ensure reliable results were acquired. Data for relative permittivity and dielectric loss tangent of the ABS material are shown in Fig. 3 By changing the infill percentage, the effective dielectric properties are a combination of the host ABS material and air.

Fig. 2. Photos of samples with different infill fractions for the SPDR measurements

Analysing results obtained in Fig. 3a, it can be concluded that relative permittivity of ABS material increases linearly with increase of material infill percentage at both tested

frequencies. This result validates assumed hypothesis of increasing volume factor affecting relative permittivity in a linear manner, as varying infill volume percentage affects the average permittivity throughout each sample. Fig. 3b also shows that increasing infill volume percentage results in linear increase of loss tangent at frequency of 1.9GHz, which marginally vary from results obtained at frequency of 2.4GHz. All materials exhibited low losses.

Fig. 3a. Effects of varying infill percentage on relative permittivity of ABS material

Fig. 3b. Effects of varying infill percentage on dielectric loss tangent of ABS material

III. 3D PRINTED HETEROGENEOUS SUBSTRATES

In this paper, 3D printed heterogeneous substrates have been investigated. Variance of relative permittivity as a function of substrate location had an effect on altering the manner in which the electric field were distributed due to non-uniform architecture of the substrate when compared to the homogenous antenna substrate. Four different substrate designs were considered in this report. Two of the designs altered the relative permittivity along x and y axis, using eight strips measuring 80mm by 10mm to construct 80mm (w) $\times$ 80mm (l) substrate with thickness of 1.524mm (h). The two designs were: linear increments of the relative permittivity

along y axis with horizontally placed strips, Fig. 4(a), and linear increments of relative permittivity along x axis with vertically placed strips, Fig. 4(b). The feeding point is shown as “PIE” in the figures.

Figure 4(a) Illustrating linear increments of relative permittivity along y axis with horizontally placed strips and Fig. 4(b) illustrating linear increment of relative permittivity along x axis with vertically placed strips.

In the remaining two designs relative permittivity was altered along z axis with use of five 80mm (w) $\times$ 80mm (l), 0.3048mm (h) thin homogenous substrate planes, where relative permittivity was linearly increased along z axis, Fig. 5(a) and vice versa Fig. 5(b).

Figure 5(a) Illustrating side view of substrate permittivity varied along z axis, where bottom to top layer ϵ_r values are respectively: 1.8, 2.4, 3, 3.6 and 4.2 and Figure 5(b) where bottom to top layer ϵ_r values are respectively: 4.35, 3.75, 3.15, 2.55 and 1.95

In order to investigate the effect of heterogeneous substrates in patch antennas, EMPIRE XPU finite-difference time-domain (FDTD) simulation software was used. All antenna substrate designs were designed to operate at the same frequency of 2.08GHz ($\pm 1\%$) to allow a fair comparison as the electrical substrate thickness was kept constant. For each design the feed point was moved to ensure the antennas were well matched. The relative permittivity of the homogenous substrate was 2.9 and the loss tangent was 0.003. Results are shown in Table I. The loss tangent of all the materials was assumed to be 0.003,

Table I Simulated antenna performance comparison at first and second resonance with various heterogeneous substrate designs

Substrate Design	f_0 (GHz)	S_{11} at f_0 (dB)	f_0 -10dB BW (%)	f_0 Radiation Efficiency (%)	f_0 Total Efficiency (%)	f_0 Directivity (dBi)	f_1 (GHz)	f_1 Radiation Efficiency (%)	f_1 Total Efficiency (%)	f_1 Directivity (dBi)
Homogenous	2.06	-30.9	1.36	78.5	78.3	6.78	3.48	81.7	71.3	7.71
Horizontal strips	2.10	-27.9	1.59	74.1	62.5	6.82	2.97	62.5	46.1	5.42
Vertical strips	2.07	-26.3	1.18	55.7	55.5	6.77	3.38	78.7	75.8	7.65
Z axis variation (increasing)	2.09	-37.8	1.33	82.1	82.1	6.88	3.56	83.7	74.1	7.69
Z axis variation (decreasing)	2.08	-30.5	1.36	82.8	82.7	6.79	3.53	83.2	72.9	7.72

Review of performance parameters in Table I concluded that proposed designs had no major advantage in improving performance of patch antenna. If the frequency was kept constant, then the performance was similar except for the vertical strips. Changing the relative permittivity locally changed the ratio of the first and second resonance. Investigating obtained results of feed position against S_{11} response, it was concluded that a novel response was formed, whereby linear variation of permittivity throughout substrate along y axis lead to prospect of achieving improved match for second resonant frequency when compared with homogenous substrate antenna. It was identified that variation of permittivity along width of substrate resulted in shifting and improving response of the second resonance due to alteration of electric fields along width of patch which primarily dictate behaviour of second resonance. Proposed design was validated by comparison of simulated and measured results.

IV. 3D PRINTED ANTENNA SUBSTRATES

A heterogeneous substrate was 3D printed in one process where the relative permittivity was locally varied. GTS copper sheets were glued to the substrate for the metal parts. Two different feed points were considered to investigate the matching at the first and second resonance. 11mm from the left hand side feed point was chosen to validate good match for first resonant frequency and 8mm to validate capability of achieving good match for first and second resonant frequencies. Heterogeneous substrate patch antenna dimensions are presented in Fig. 5, where substrate thickness was 1.524mm (h). Homogenous substrate patch antenna was fabricated using identical dimensions as Fig. 5.

Fig. 5 Dimensions of heterogeneous substrate patch antenna

Fig. 6, Photo of homogenous substrate antenna; heterogeneous antenna feed point located 8mm from the edge and heterogeneous substrate antenna with feed point located 11mm from the edge

Measurements of prototypes presented in Fig. 6 were carried out in an anechoic chamber. Simulated and measured results of patch antenna S_{11} responses, efficiencies, directivities were studied and are presented in Table II. The S_{11} results are shown in Fig 7. Radiation patterns of the heterogeneous prototype antenna have been measured and presented in Fig. 8.

Table II The S_{11} , radiation efficiency and directivity for design A (homogenous substrate antenna), design B (heterogeneous antenna substrate with 8mm feed position) and design C (heterogeneous antenna substrate with 11mm feed position)

Antenna design	Simulated f_0 (GHz)	Measured f_0 (GHz)	Simulated S_{11} (dB)	Measured S_{11} (dB)	Simulated Radiation Efficiency (%)	Measured Radiation Efficiency (%)	Simulated Directivity (dBi)	Measured Directivity (dBi)
Design A	2.06	2.08	-25.9	-23.2	78.5	71.3	6.78	7.12
Design B	2.10	2.08	-11.46	-13.78	76.0	64.1	6.82	7.01
Design C	2.10	2.09	-27.85	-17.69	74.1	68.4	6.82	6.94

Fig. 7 Measured and simulated S_{11} of homogeneous substrate; heterogeneous substrates with 8 feed point and heterogeneous substrate with 11mm feed point

Fig. 8 Measured and simulated radiation patterns at frequency of 2.08 GHz for heterogeneous substrate antenna with 11mm feed point

Analysing results recorded in Table II, it can be concluded that all three antenna design measurements show strong correlation with simulated data.

V. CONCLUSION

This paper has demonstrated that substrates with different relative permittivities can be created using 3D printing. The material had a low loss tangent. This provides extra degrees of freedom in terms of relative permittivity, thickness and potentially 3D shapes. The relative permittivity varied approximated linearly with the infill volume fraction. Substrates were printed in one process where the permittivity varied locally. Simulation studies indicated that generally, the overall performances of the antennas were similar as long as the antenna was designed to operate at the same frequency. However, the ratio of the first and second resonance frequencies varied as the location of the permittivity regions changed with respect to the electric fields at each resonance. Heterogeneous substrates were used to improve the S_{11} at both resonances.

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