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Applications and Future Prospects for Microstrip Antennas Using Heterogeneous and Complex 3-D Geometry Substrates

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Abstract—This paper critically reviews the electromagnetic advantages of altering the dielectric substrate section of the antenna as opposed to the conducting elements. Changing the dielectric has been used to improve the bandwidth, efficiency and gain of antennas. Heterogeneous substrates have also been employed to lower the effective permittivity, suppress surface waves for high indexed substrate materials and reduce mutual coupling. In the second half of this paper, 3-D printing has been used to create substrates with reduced material consumption for a lightweight flexible wearable antenna.

1. INTRODUCTION

Consumer demand for small devices with wireless connectivity has put increasing pressure on antenna engineers to improve electromagnetic performance in smaller packages. These design constraints are further exacerbated by increasing demand for improved bandwidth, efficiency and frequency coverage. Including an additional degree of design freedom by manipulating the substrate shape and properties can help address these challenges. These synthetic substrates are very difficult to manufacture using conventional technologies. Complex 3-D printed geometries can easily be manufactured from computer aided design models that can be exported directly from electromagnetic simulation software. 3-D printing allows the geometry to be varied in all three dimensions, therefore printed cavities of various shapes and sizes can lead to a smooth or discrete change in the effective permittivity. With the latest advances in additive manufacturing and 3-D printing, the antenna and radiofrequency designer will be able to control the local effective permittivity and the substrate shape to gain electromagnetic advantages.

Section 1 of this paper reviews the advantages of using heterogeneous substrates. Section 2 investigates the minimisation of the substrate volume. Section 3 details how these samples can be manufactured using 3-D printing. Conclusions are drawn in Section 4.

1.1. Control of Surface Waves and Current Modes

Microstrip antennas are light, low profile, conformal, compact structures which are normally fabricated on a homogeneous substrate. They can be regarded as a dielectric filled parallel plate waveguide radiating at discontinuities [1, 2]. The size of an antenna can be easily reduced by using a dielectric with a high-valued permittivity but this also increases the energy in the surface wave modes [3]. These surface waves decrease the efficiency of the antenna and also cause interference with the radiation pattern by getting diffracted from the edges of the finite sized ground plane [4]. These detrimental effects can therefore be reduced by suppression of surface wave modes. Heterogeneous substrates have been utilised, for a circular microstrip antenna, to completely suppress the surface waves caused by TM_0 mode, which is the main cause of surface wave radiation for thin substrate microstrip antennas [4]. The

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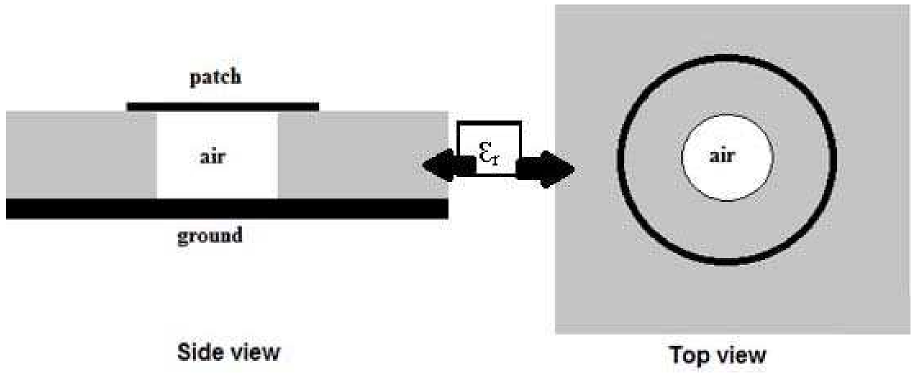


Figure 1. An air filled cored patch. The dark circle shows the boundary of the patch in the top view (redrawn from [4]).

equivalence principle and cavity model allow the radiation patterns of a circular patch to be computed by considering it as a magnetic current ring. When the radius of this magnetic current ring is the same as the radius of the circular patch surface waves caused by the TM_0 mode are then completely suppressed [5]. The radius of this ring was however larger than that for a typical patch, so an air cavity as shown in Figure 1 was introduced at the centre of the patch. This cavity decreased the effective dielectric index of the substrate, as the cavity was air-filled ($\varepsilon_r = 1$), leading to an increase in the size of the patch. The size of the patch is now equal to the magnetic current ring thus fulfilling the above condition for surface wave suppression and improving the radiation pattern of the antenna as a result [4]. This technique was also applied to a rectangular patch for surface wave suppression [6].

The cored patch design was also applied to a microstrip antenna array in order to reduce the side lobe level, a characteristic coveted for radar applications and achieved by reduction of mutual coupling and surface waves [7]. A further reduction in side lobe level was obtained by introducing narrow metallic strips between the air-cored array elements [7]. Previously the author of this paper has been able to control the multi-band performance of the antenna by introducing air cavities at the radiating edges of the patch [8]. Heterogeneous substrates, prepared by removing the substrate surrounding the patch, partially and completely, have been used to increase the gain of a microstrip antenna by supressing the surface waves [9]. Substrate removal has also been applied to a cavity backed slot antenna and provided an improvement in its bandwidth and efficiency [10].

1.2. Etched Substrates to Control Local Permittivity

Another example of the benefits of varying the substrate geometry can be found in Monolithic Microwave ntegrated Circuits (MMIC) technology which allows the antennas to be integrated with other components of millimetre and microwave circuits [11]. High dielectric index increases the energy in the surface waves and also decreases the bandwidth of the antenna [3]. The use of thick substrates alleviates the bandwidth problem but increases the surface wave energy [3, 12]. A solution to the problem lays in hybrid integration schemes, where the antenna is on a material of low permittivity in contrast to the other components of the circuits but this approach increased the cost [13]. So a micro-machined antenna, in which chemical etching was used to remove a large portion of silicon from beneath the antenna (as shown in Figure 2), was proposed [13]. The dielectric index of this newly formed structure of air-silicon substrate can be computed by utilising the cavity model [13]. An effective permittivity of 2.8 was obtained by removing half the silicon by volume below the antenna in [12] an dielectric constant of 2.2 was obtained which led to an improvement in the antenna efficiency and bandwidth [13]. Mutual coupling among various antenna array elements was also improved by changing the dielectric index using micromachining [11]. Another design employed backside etching for removal of silicon below the radiating edges of the patch and caused a decrease in the value of the effective permittivity of the substrate [14]. Micromachining was also applied to increase the gain of an antenna where the patch was placed at the interface of the superstrate and micromachined air cavity [15].

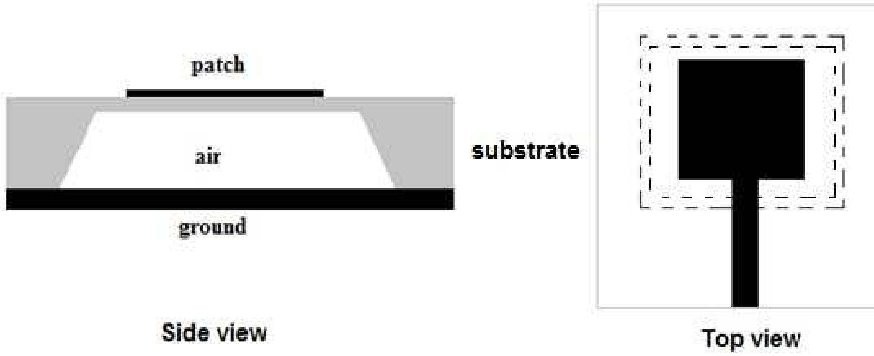


Figure 2. A micromachined patch antenna. The dotted boundary in the top marks the start and the end of the slanted edges. The edges are slanted due to anisotropic chemical etching (redrawn from [13]).

The conductive properties of silicon decrease the antenna efficiency, so a thin film of SiO_2 was deposited on the top of the micromachined substrate to reduce the substrate losses [16, 17]. Micromachined substrates with a SiO_2 layer have been used for both, a patch and a meandered dipole to improve the efficiency and bandwidth of the antenna, and reduce the effective permittivity [16, 17]. The efficiency of a differential fed dipole on a low resistive silicon substrate was improved by micromachining in such a way that the middle portion of the silicon was etched away and the newly formed cavity was then filled with SU8 photoresist, which isolated both silicon sections and also provided support to the SiN (Silicon Nitride) layer placed at the top of the substrate [18]. Another antenna where the shallow etched cavity, directly below the patch, was filled with SiO_2 and polyimide was presented in [19].

1.3. Heterogeneous Substrates Prepared by Drilling Holes

The effective permittivity of a high indexed dielectric (Duroid 6010) was reduced from 10.8 to 2.3 by drilling small periodic holes in the slab [20]. This synthesized material was then used to improve the bandwidth and efficiency of an antenna [20]. Similarly holes were drilled in the middle layer of a three layered stacked patch to reduce this layer's permittivity [21, 22]. This provided sturdiness to the structure of the antenna without compromising the performance [21]. It was also observed that the synthesized heterogeneous dielectric behaved similarly to a low permittivity homogenous substrate [20, 22]. The permittivity of the substrate surrounding an antenna on a thick, high indexed dielectric was lowered via drilling holes in the structure, which suppressed the surface waves and thus caused an improvement in the radiation pattern without causing any reduction in the bandwidth [3]. The process of drilling holes for lowering the permittivity was also applied to tapered slot antenna with the purpose of increasing the effective thickness of the substrate, hence adding sturdiness to the structure [23]. Synthesized dielectrics with both small and large sized holes produced identical radiation patterns [23]. Rotman lenses [24] are an important component of many beam forming networks and have been utilised in various applications including multi-beam receivers, beam steering antenna systems and automotive radar systems [25, 26]. Heterogeneous dielectrics have been employed to reduce the insertion loss in comparison with a homogeneous substrate Rotman lens. A gradient of permittivities, as indicated in Figure 3(a), was synthesized by varying the density of drilled holes in the substrate and used to bend the rays with in the lens for improved focussing. This also decreased the power loss due to spill-over to the side ports [26]. Layered heterogeneous substrates, as in Figure 3(b), were synthesized using low temperature co-fired ceramics (LTCC) processing. Materials with a reduced loss tangent compared to the parent material were obtained and then utilised to realise filters with comparatively lower insertion losses [27]. Heterogeneous dielectrics with permittivity varied by drilling holes in a slab have also been used in transformation optics for synthesizing a flat lens which then is used to enhance the directivity of a dielectric sheet resonator [28].

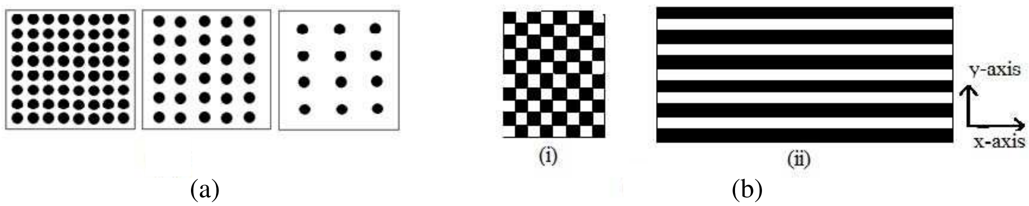


Figure 3. (a) A perforated dielectric slab where the density of air-filled holes varies the effective permittivity (redrawn from [26]); (b) the darker part indicates the section from which the substrate has been removed. The direction of electric field is along z-axis for (i) and y-axis for (ii) (redrawn from [27]).

1.4. Composite Structures

Composite structures are formed when materials with two different permittivities are combined yielding a bespoke effective dielectric index not readily available [29, 30]. In [29], such structures are synthesized by drilling holes in a slab of barium nitrate ($\varepsilon_r = 30$) and then filling these with Bi-Ba-Nd-Titanate (BBNT; $\varepsilon_r = 100$), to attain an effective permittivity of 46.

The effective permittivity of a material can also be tailored by introducing dielectric and metallic micro-scale inclusions inside a homogeneous material [31, 32]. By varying the density of the inclusions, the local effective permittivity can be controlled.

1.5. 3-D Antennas and Substrates: Advantages and Fabrication

The advent of additive manufacturing (AM) techniques such as 3-D printing now enables any shape with intricate internal/external geometry to be created directly from a computer aided design (CAD) file. Currently, there are a wide range of polymers suitable for 3-D printing and these have a range of physical properties. 3-D printing can also be used to create flexible substrates. Furthermore, holes can be included to allow the antenna to be breathable for wearable applications. By leaving gaps in the CAD model — heterogeneous structures with air as the 2nd material can be considered. This has direct relevance for various antenna systems. Emerging AM techniques allow multiple materials to beprinted and in the near future, dielectric and metallic structures will be created by the same AM machine. Therefore, elaborate miniaturised 3-D antenna geometries can be considered. 3-D printing can potentially reduce costs by only using material additively and by reducing the number of fabrication processes.

The author has previously shown that 3-D substrates can be used to decrease the antenna size by exploiting the non-uniform electric fields of a patch antenna [33].

2. ANALYSIS OF SUBSTRATE REMOVAL

2.1. Geometry

Microstrip patch antennas are popular as they planar and can be placed close to other objects including the human body as in wearable applications. Generally, the substrate exists over the entire ground plane which can add unnecessary weight and cost. It is widely known that the electric fields are not uniformly distributed below the patch antenna and therefore the substrate does not have to be uniform. The electric fields can be seen in Figure 4. With a feed on the left hand side — the electric fields in the substrate are largest at the sides of the patch and minimum at the centre of the patch.

The geometry of the patch antenna used in this work is also shown in Figure 4. The substrate is 3 mm thick. One of the advantages of 3-D printing is that the dimensions can be chosen for bespoke designs and the antenna designer is no longer limited to existing materials and dimensions. To verify the material properties a patch antenna with a substrate was fabricated using 3-D printing and the measured S_{11} was compared to simulations, see Figure 5. In this paper, EMPIRE XCcel finite-difference time-domain (FDTD) software was used for analysis and simulations. The material was found to have a relative permittivity = 2.72 and tan delta = 0.025.

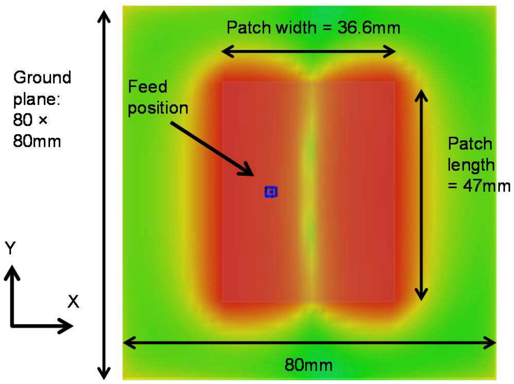


Figure 4. Geometry and dimensions of the patch antenna with a plot of electric field intensity in the substrate.

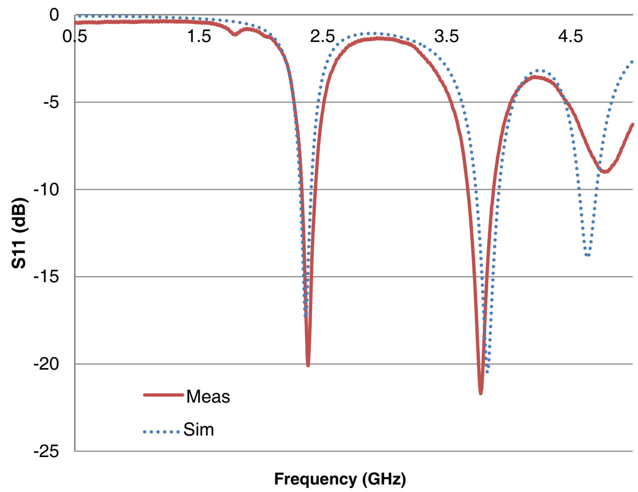


Figure 5. Measured and simulated S_{11} response illustrating the impedance match of original patch design.

2.2. Effect of Substrate Reduction on Patch Dimensions

The aim of this section was to minimise the substrate volume without affecting the frequency hence only the S_{11} parameter was monitored. As a first step to minimise the volume, the width and length of the substrate were varied in the simulation software and the resonant frequency was recorded. The effect of the width is shown in Figure 6. When the full width is 80 mm, the frequency of the antenna is 2.37 GHz. Reducing the substrate width has a minimal effect until the width approaches approximately 40 mm. Further reductions to the substrate width, increase the frequency. The central region of the substrate along the X direction can also be removed without affecting the frequency as the electric fields in this region are small.

The results for varying the substrate length are shown in Figure 7. The substrate beyond the patch in the Y direction can be removed without affecting the frequency. Removing the substrate within the length of the patch linearly increases the frequency.

Combining the results in Figure 6 and Figure 7, the substrate can be reduced in size in both the

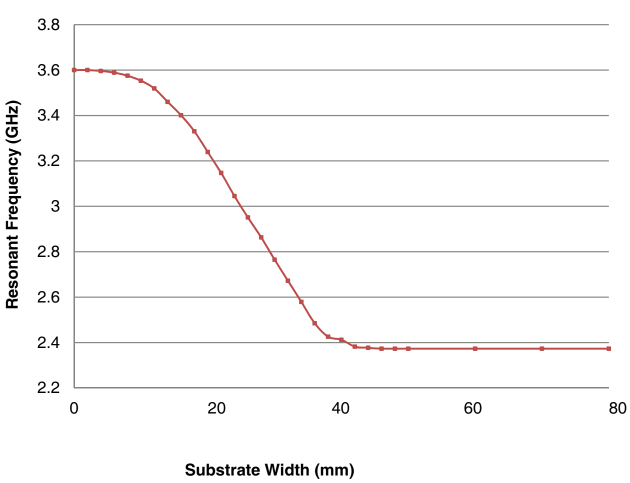


Figure 6. Simulated results of varying the substrate width (X direction).

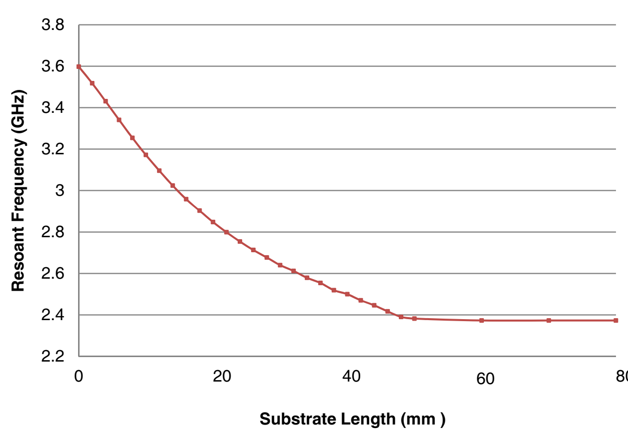
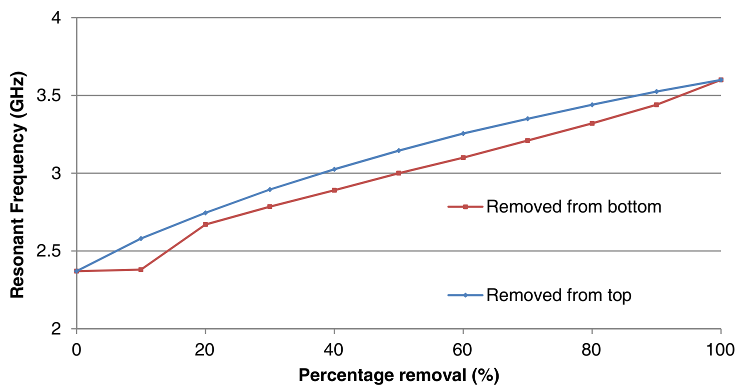


Figure 7. Simulated results of varying the substrate length (Y direction).

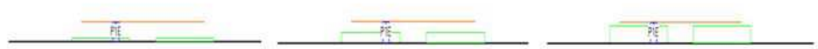
X and Y directions. For the original patch size of 36.6×47 mm, the substrate can be reduced to 42.6×49 mm whilst the frequency increase by less than 1% compared to the original design. Therefore, a larger width of substrate in the X direction in relation to the patch size is required compared to the length in the Y direction. Furthermore, a central width of 7.8 mm of the substrate in the X direction can also be removed. Therefore, for the original design in Figure 4, the 80×80 mm substrate can be reduced to two blocks of 17.4×49 mm with a centre gap of 7.8 mm. The substrate volume was reduced by 73% from $80 \times 80 \times 3$ mm to $2 \times 17.4 \times 49 \times 3$ mm while the frequency changed by less than 1%.

2.3. Effect of Substrate Height Reduction

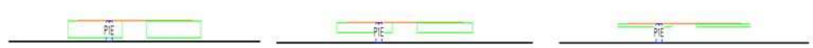
3-D printing allows material manipulation in all three dimensions. In this section, the effects of variation of the substrate height are investigated by simulations. Two possibilities are considered: i) removing the substrate at the top of the patch antenna and ii) removing the substrate from the bottom where the substrate is touching the ground plane. The geometry and results are shown in Figure 8. The results indicate that the frequency increases linearly as the substrate is removed. The dielectric loading of the patch and hence the frequency reduction is slightly stronger with the substrate close to the patch as the fields are not uniform in the Z direction. The effective permittivity of a dual layer substrate is approximately the volume average of the two layers and the internal structure is a secondary consideration.



(a)



(b)



(c)

Figure 8. Simulated results with variation in substrate height. (a) Removing substrate from top and bottom; (b) substrate removed from top and (c) substrate removed from bottom.

Figure 4 shows that the electric fields in the X direction are at a maximum at the edges of the patch and decrease as we move towards the centre of the patch. 3-D printing can create internal triangular sections where the effective permittivity varies with the volume average of air and the original material. Six different geometries were considered for triangular substrate sections in the X-Z plane as shown in Figure 9 and the results of frequency as a function of volume fraction are shown in Table 1. The frequency increased with removal of the triangular substrate sections with a slightly larger effect when the substrate was removed from the top.

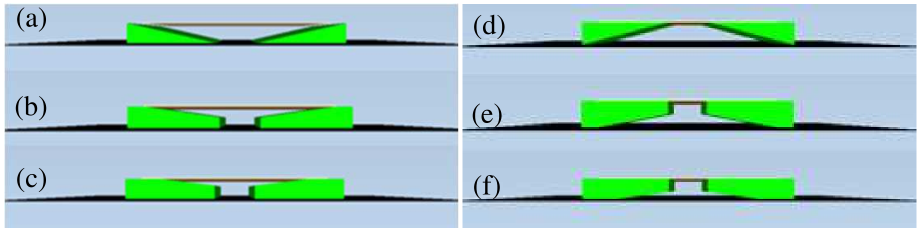


Figure 9. Triangular sections of substrate removed: (a)–(c) from top; (d)–(f) from bottom.

Table 1. Simulated results with triangular sections removed.

Geometry	Volume fraction removed (%)	Frequency (GHz)
Figure 9(a)	50.0	3.05
Figure 9(b)	20.8	2.61
Figure 9(c)	10.2	2.47
Figure 9(d)	50.0	2.87
Figure 9(e)	20.8	2.60
Figure 9(f)	10.2	2.45

3. 3-D PRINTED SUBSTRATES

In Section 2, the effect of the substrate was examined on the resonance frequency. In this section, the final sample will be created using 3-D printing technology. It is important to note that the manufactured substrates are flexible and are particularly attractive for wearable applications. Therefore, minimising the volume can reduce cost, weight and the volume of the antenna when it is packaged or folded when not is in use. Holes were incorporated into the prototype design to allow the material to be breathable. A hole for the connector pin was also included in the CAD design for easy of probe feed assembly. Additional dielectric legs were added below the thinner substrate section at the centre of the patch (in the X direction) to provide additional support to the metallic patch. The geometry of the antenna as created in EMPIRE XCcel is shown in Figure 10. Note the patch was continuous but is shown as transparent to show the holes in the substrate. The geometry created in the electromagnetic software can be directly exported to the Connex 500 3-D printing machine. The ground plane and patch were made from thin copper sheets but other conductive textiles such as Nora Dell could also be used to

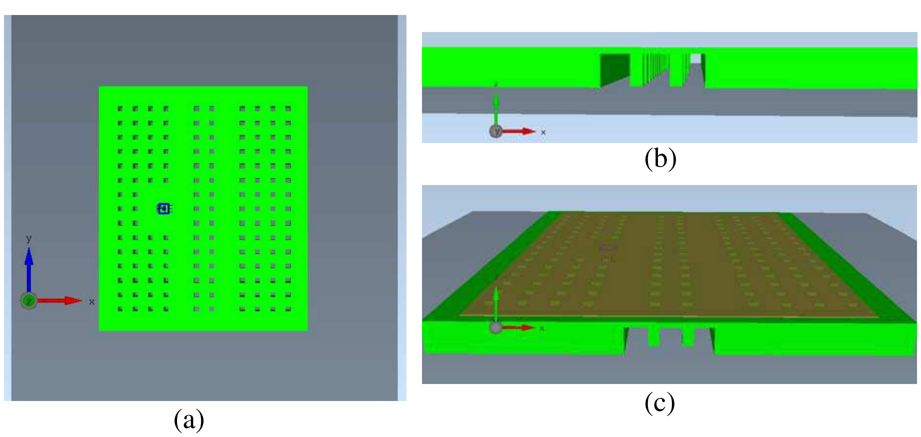
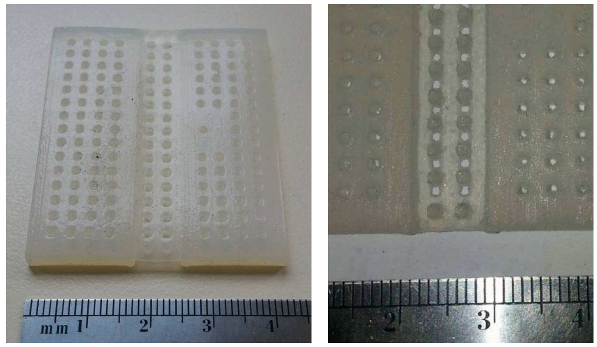


Figure 10. Geometry of final design. (a) Top view of final design of substrate with holes; (b) side view showing legs supporting the central structure and (c) including patch (the patch is continuous but is transparent to show the holes in the substrate).



(a) (b)

Figure 11. 3-D printed substrate. (a) Top view; (b) legs under central section.

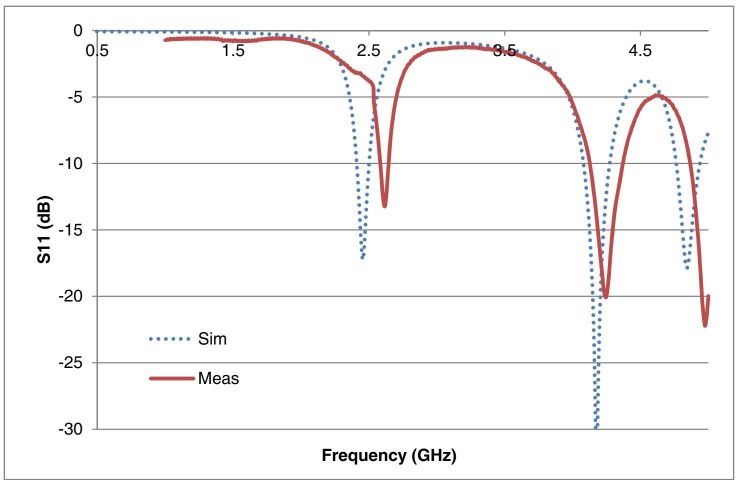


Figure 12. S_{11} of final design.

maintain the breathability and flexibility. The 3-D printed substrates are shown in Figure 11. The S_{11} results are shown in Figure 12. The frequency compared to the original design has increased due to the holes in the substrate near the edges of the patch. Depending on the required geometry, the number of holes could be reduced to maintain the original frequency.

4. CONCLUSIONS

This paper has described and discussed three different aspects in this emerging technology: i) a critical review of heterogeneous substrates; ii) provided an analysis of the effects of reducing the substrate volume and iii) outlined a wearable patch antenna design example using a novel flexible substrate manufactured via 3-D printing. Heterogeneous substrates have been previously used to lower the dielectric index of the structure locally and to improve the bandwidth and efficiency of different antenna structures. They are also used for elimination and reduction of surface waves and increase the gain of an antenna. Conventionally, these heterogeneous substrates are prepared by the removal of a section of dielectric from the homogenous slab through etching and the drilling of voids.

It has been established here that volume of substrate can be significantly reduced to approximately the size of the patch and does not have to cover the whole ground plane. The extra substrate surrounding the patch in the resonant mode direction was seen to be more important than in the length of the patch. This observation will in general be true for other modes excited and patch geometries. Significantly the study found that the substrate material volume could be reduced by 73% while approximately maintaining the original frequency. However, as anticipated the frequency is very sensitive to the reduction in the substrate material as a function of the height of the antenna.

3-D printing is an emerging technology that is now becoming affordable to the general public and desktop 3-D printers are becoming increasingly common. Therefore, 3-D printing offers a simple fabrication method for creating complex geometries that can facilitate electromagnetic advantages. Different materials with different physical and electrical properties are possible. Bespoke heights are possible as are 3-D structures tailored to the electric field configuration. The fabrication process can be used for one off designs, a series of bespoke design or many identical units which enables manufacturing scalability. Production cost may be further reduced by adoption of software standards and protocols that export the CAD files to additive manufacturing hardware. Electromagnetic advantages are possible by varying the effective permittivity of the substrate-air internal geometry. Physical features can also be introduced for style, structural support or to minimise the number of fabrication processes. The next generation of additive manufacturing techniques will be able to fabricate antennas using dielectric and metals in one process and this likely to stimulate the creativity of the antenna designer and accelerate this technology adoption by industry.

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