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Multilayer and Conformal Antennas Using Synthetic Dielectric Substrates

Enrique A. Navarro, Avinash Luximon, Ian J. Craddock, Dominique L. Paul, and Michael Dean

***Abstract*—Multilayer antennas—for example, stacked patches—often employ low permittivity substrates, such as foams. These foams, however, tend to be fragile, difficult to glue, and difficult to bend. In a previous contribution, the authors described how a Duroid substrate may be drilled in order to obtain a low permittivity synthetic dielectric. This paper shows, by means of both practical and numerical experiments, the results of using such a substrate in a range of multilayer antennas.**

***Index Terms*—Conformal, finite-difference time-domain (FDTD), multilayer antennas, synthetic dielectric.**

I. Introduction

Stacked patch antennas commonly employ three layers of substrate, with the central layer having a relative permittivity close to unity. This layer is often made from foam (in [1], for example, a low dielectric foam with $\varepsilon_{\rm r} = 1.07$ is recommended for optimum bandwidth), but this is usually fragile, difficult to cut, bend, and glue, and unable to support a metallization An air-gap is an alternative, but this requires spacing elements [2] that complicate manufacture and reduce strength.

A previous investigation by the authors [3] demonstrated how a low dielectric constant material can instead be obtained by drilling a lattice of holes in a standard Duroid substrate $(\varepsilon_{\rm r} = 2.2)$. This is a practical technique for small antennas since numerically controlled machines can be used to drill the holes. In [3], this "synthetic dielectric" was employed as the substrate of a simple single-layer patch—multilayered antennas were not considered. The objective, however, was always to employ the material in a multilayer patch.

This paper therefore presents the application of the concept in the design of various stacked patch antennas. Numerical results from a range of stacked patch antennas using different synthetic substrates are presented and their input and far-field responses compared to results from a stacked patch antenna using a central layer of low dielectric foam. The drilled Duroid is especially useful for conformal designs since the substrate will bend (unlike many foam materials). This is also demonstrated here by presenting practical results for both conformal and planar stacked patches.

II. Methodology

To a first approximation, a substrate with electrically small holes might be expected to behave as though it were a synthetic dielectric—a solid substrate with an average dielectric constant (although it might also exhibit other behavior). The working frequency of the resulting antenna could then be obtained by assuming this dielectric constant and employing numerical, semianalytical, or empirical formulas [4].

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E. A. Navarro is with the Department of Applied Physics, Universitat de Valencia, 46100 Burjassot, Valencia, Spain.

A. Luximon, I. J. Craddock, and D. L. Paul are with the Department of Electrical and Electronic Engineering, University of Bristol, BS8 1UB Bristol, U.K.

M. Dean is with DERA, WR14 3PS Malvern, U.K.

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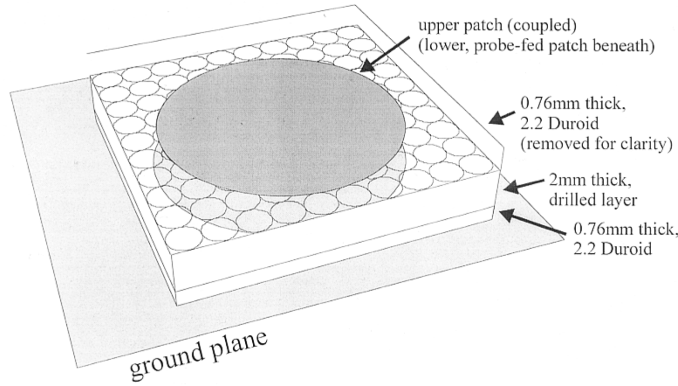

Fig. 1. FDTD model of circular stacked patch design with drilled substrate.

If a *square* lattice of circular holes is employed, the average dielectric constant ε_r(av) would be

$$\varepsilon_r(\text{av}) = \frac{\varepsilon_r \cdot (d^2 - \pi \cdot a^2) + \pi \cdot a^2}{d^2}$$

whereas for an equilateral *triangular* lattice

$$\varepsilon_r(\text{av}) = \frac{\varepsilon_r \cdot (d^2 \cdot sin60 - \pi \cdot a^2) + \pi \cdot a^2}{d^2 \cdot sin60}$$

where d is the distance between holes in the square lattice, a is the radius of each hole, and $\varepsilon_{\rm r}$ is the substrate relative permittivity (generally 2.2 in the authors experiments). Obviously, for a hole radius a and distance d between holes, the triangular lattice produces a lower dielectric constant because of a higher filling factor of the holes.

The major drawback of a microstrip patch antenna in its basic form is its inherently narrow bandwidth. The *stacked* patch antenna is designed with the idea that two coupled patches will resonate at different frequencies, close to each other, and this frequency response will provide the desired bandwidth.

In order to obtain a good input bandwidth, a low permittivity material is often recommended as the central layer of the stacked packed patch [1]. However, low dielectric constant materials, such as foams, often have disadvantages as described above. It was shown in [3] that a range of low dielectric constant materials can be achieved by drilling a lattice of holes in a standard Duroid substrate with $\varepsilon_{\rm r} = 2.2$.

Now some questions arise.

1) Will the drilled Duroid be a satisfactory replacement for a true low-dielectric foam in the stacked patch?
2) The ε_r(av) will be dependent upon the filling factor of each unit cell. Thus, can we expect the same results for different dimensions that have the same ε_r(av), i.e., the same filling factor?

These questions are answered in the following sections by means of numerical and practical experiment.

III. Numerical Validation

An finite-difference time-domain (FDTD) model of a three-layer circular stacked patch design (Fig. 1) was initially specified. The lower and upper substrates have $\varepsilon_r = 2.2$, separated by a low-permittivity synthetic dielectric substrate. Thirteen models were used to evaluate the effect of changing the radius of the holes and the dimensions of

TABLE I
COMPARISON OF FREQUENCY BANDWIDTH OF CIRCULAR STACKED PATCH ANTENNA DESIGNS FOR SOLID AND VARIOUS DRILLED SUBSTRATE LAYERS

Antena	$\varepsilon_r(av)$	lattice	d (mm)	a (mm)	holes under the patch	10dB bandwidth (f_1-f_2)	10dB bandwidth Δf
0 original	1.2	solid	--	--		8.8-10.5	1.7
1	1.6	□	5.6568	2.078	2×2 holes	8.2-8.9	0.7
2	1.5968	□	5.0	2.078	3×3 holes	8.55-9.95	1.4
3	1.2575	□	5.0	2.5	3×3 holes	8.9-10.7	1.8
4	1.5968	□	3.0	1.2	5×5 holes	8.5-9.5	1.0
5	1.2575	□	3.0	1.5	5×5 holes	8.8-10.5	1.7
6	1.5968	□	1.5	0.6	10×10 holes	8.45-9.4	0.95
7	1.2575	□	1.5	0.75	10×10 holes	8.8-10.5	1.7
8	1.5968	□	1.5	b=1.0634	10×10 square holes	8.45-9.3	0.85
9	1.4252	□	3.75	1.7	4×4 holes	8.7-10.1	1.4
10	1.2575	□	3.75	1.85	4×4 holes	8.8-10.5	1.7
11	1.3054	△	3.75	1.7	--	8.75-10.35	1.6
12	1.1117	△	3.0	1.5	--	9-10.8	1.8
13	1.1117	△	1.5	0.75	--	9-10.8	1.8

the square or triangular lattice. The results of this investigation are presented in Table I—the goal being to obtain an antenna that has the same performances as the original stacked patch antenna with a solid central substrate of $\varepsilon_r = 1.2$ (model 0).

Models 3, 5, 7, and 10 have similar performance to model 0—the return loss of antennas 5, 7, and 10, matching almost exactly the return losses of the original antenna. However, a wider bandwidth is achieved by antenna 3, although the response is slightly shifted 0.1 GHz to higher frequencies, probably as a result of the large holes (nine holes) only located under the patch. With antenna models 12–13, we get an even wider bandwidth, and shift in frequency, mainly because the synthetic dielectric is $\varepsilon_r = 1.1$. This is slightly lower than that of our original antenna (number 0), which uses a foam having $\varepsilon_r = 1.2$.

So far, in order to obtain the same return loss as the original antenna, we have to make holes in the substrate in order to obtain an average ε_r value that is the same as the desired antenna. As long as ε_r(av) approximates $\varepsilon_r = 1.2$ of the ideal antenna, the same return loss is obtained. By increasing the filling factor of the holes further, as is seen in cases 12 and 13,ε_r(av) is further reduced, producing a slightly different behavior with a wider bandwidth. The dimensions of the square lattice and radius of the holes do not seem to matter as long as the same ε_r(av) is achieved. Fig. 2 shows S_{11}, for the original antenna with foam (model 0), and for a selection of antennas with synthetic dielectrics (models 3, 5, 7, and 10).

There is also no appreciable influence in the radiation pattern (calculated at the center frequency of 9.65 GHz). The levels of cross-polarization are the same as those found in the original design. These results are presented in Fig. 3. Similar results were obtained for the other synthetic dielectric antennas having the same ε_r(av) and different lattice (square-triangular).

IV. EXPERIMENTAL VALIDATION

Attention is now turned to experimental validation of the approach, this time (for ease of construction) using a larger, square version of the previous modeled structure to work at around a center frequency of 4.9 GHz. Each patch was 2 cm across; all three substrates were 0.635 mm in thickness. Versions were constructed using foam (this time with a permittivity of 1.1) as the central layer and using a drilled material with ε_r(av) $= 1.588$ (using a triangular lattice, $d = 2$ mm, $a = 0.75$ mm) instead.

S_{11} results from the different versions of the antenna are shown in Fig. 4. While there are some differences (probably largely attributable

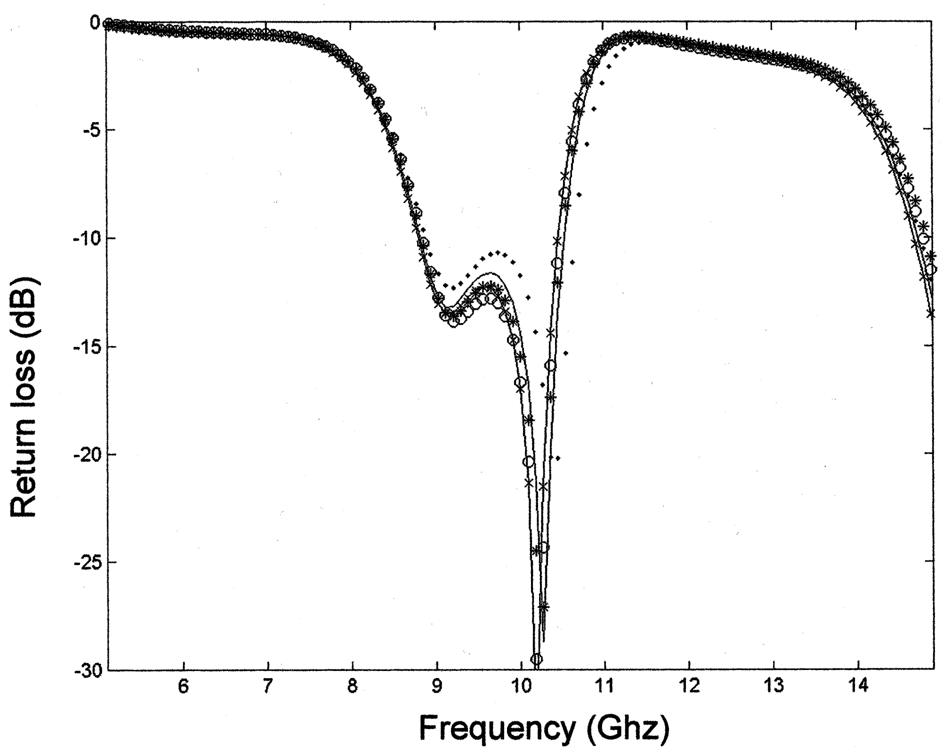

Fig. 2. Numerical (FDTD) return losses in antenna number 0 (original with foam), 3, 5, 7, and 10: (_) antenna 0-original, (.) antenna 3, ($*$) antenna 5, (x) antenna 7, ($\circ$) antenna 10.

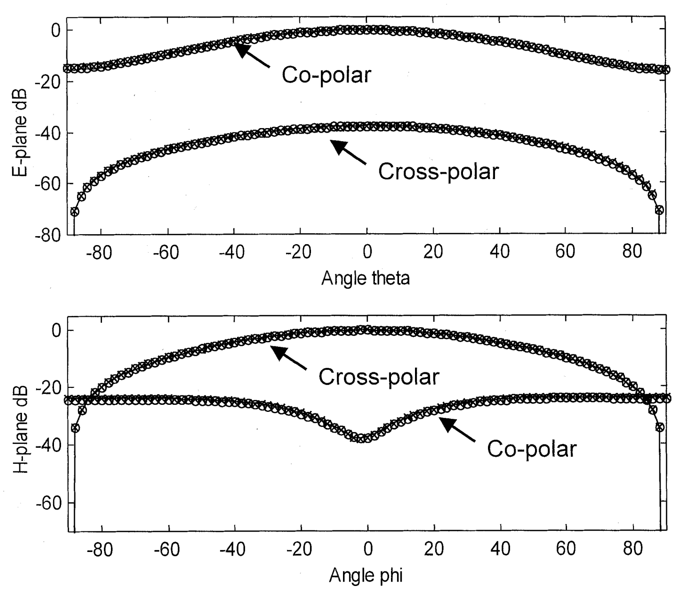

Fig. 3. Radiation pattern of antenna 0 (original with foam), 5, and 7.*Antenna 0*: *E-plane*: _ Copolar, _ Cross-polar, *H-plane*: _ Cross-polar, _ Copolar *Antenna 5*: *E-plane*: o o o Copolar, o o o Cross-polar, *H-plane*: o o o Cross-polar, o o o Copolar; *Antenna 7*: *E-plane*: xxx Copolar, xxx Cross-polar, *H-plane*: xxx Cross-polar, xxx Copolar.

to construction tolerances since such antennas are sensitive to feed position) between the antennas built using foam and those using the perforated substrate, the measured bandwidth is very similar.

Finally, the individual substrates of the square stacked patch design using the drilled substrate were heated and bent around a 6-cm-diameter cylinder. After gentle heating, the curved substrates—including the drilled material—retained their shape and could easily be glued together to form the conformal stacked patch shown in Fig. 5. $S_1 1$ data for this antenna are also shown in Fig. 4.

While none of these designs was in any way optimized for bandwidth (or input match), all offer similar and respectable (for a coaxial-fed stacked patch) figures of 13–16% for their 10-dB bandwidth.

Drilling material from a substrate weakens it. However, it has been found perfectly feasible to produce material with relative permittivities as low as 1.383 from standard $\varepsilon_{\rm r} = 2.2$ Duroid (triangular lattice with $d = 1.5$ mm, $a = 0.65$ mm). Provided that the drilled layer is adequately supported (as it is when glued to the surrounding layers), an antenna using such a material is rigid enough for most applications.

V. Conclusion

This paper has presented modeled and experimental results to support the case that drilled material can be substituted for a layer of foam or air in a stacked antenna design. By using synthetic dielectrics, several stacked patch antennas with similar performances have been demonstrated, some even better than the original foam design. The drilled material is well suited to multilayer planar antennas since it can support a metallization and can easily be cut and glued. As the material can easily be bent and retains its shape after heating, it is particularly attractive for conformal designs.

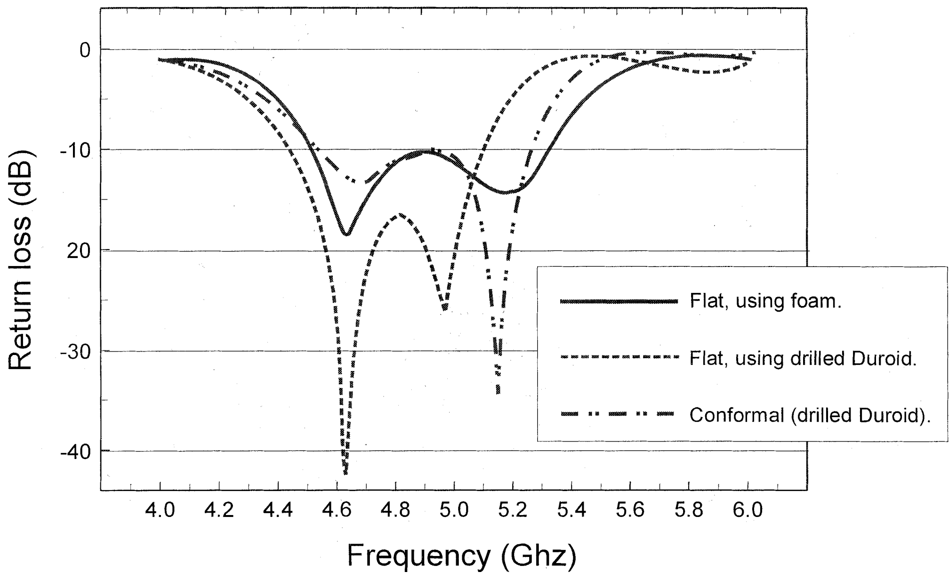

Fig. 4. S_{11} results from measurements of various square stacked patches.

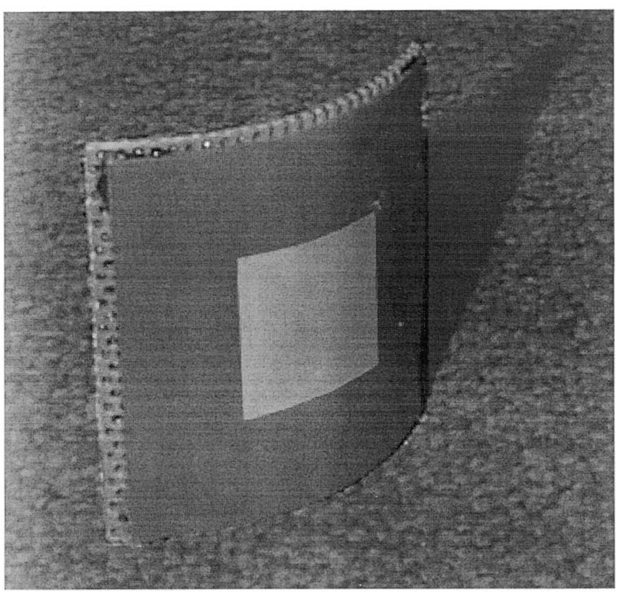

Fig. 5. Conformal square stacked patch. The dimensions of both patches are 20×20 mm^2. The substrates are 50×50 mm^2.

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Broad-Band Linear Polarization Sensor Using a Travelling-Wave Antenna

V. F. Fusco

***Abstract*—This paper shows how the tilt angle associated with a linearly polarized signal can be obtained by direct homodyne detection using a broad-band dual-port travelling-wave circularly polarized antenna. The resulting sensor would find applications in systems where polarization shift due to multipath reflections occurs and requires quantification and/or compensation. The operation of the sensor is demonstrated at 1.6–2.4 GHz and a simple analytical model given that establishes the principle of operation.**

***Index Terms*—Circular polarization, decomposition, RF sensor, traveling-wave antenna.**

I. INTRODUCTION

Modern mobile communications systems use dual slant linear polarization in an effort to combat multipath fading [1]. In practice, polarization rotation due to multiple rereflection of lossy dielectric and metallic reflecting surfaces [2] as well as the arbitrary orientation of the handset antenna mean that signal strength reception based on a slant 45° linearly polarized antenna can be much worse than if a circularly polarized antenna had been used. Reception of a linearly polarized signal received by a single-port circularly polarized (CP) antenna will result in an attendant reduction of 3 dB in received signal strength.

A simple method of extracting for a linearly polarized signal its tilt orientation γ, relative to the x axis, as defined in Fig. 1, is to use two orthogonal linearly polarized antennas. This approach relies on signal-strength manipulation and thus requires element amplitude characterization. In addition, if simple linearly polarized elements such as dipoles are used, the arrangement is inherently narrowband. In this paper, we show that by using a dual-port travelling-wave CP antenna

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The author is with the School of Electrical and Electronic Engineering, High Frequency Laboratories, BT9 5AH Belfast, Northern Ireland (e-mail: v.fusco@ee.qub.ac.uk).

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