Stacked Patches Using High and Low Dielectric Constant Material Combinations

Rod B. Waterhouse, *Member, IEEE*

***Abstract*—In this paper, the performance of stacked patches incorporating a high and low dielectric constant material combination is presented. Such a printed antenna is applicable for cases where photonic and microwave devices need to be directly integrated with the antenna. It will be shown that 10-dB return-loss bandwidths in excess of 25% can be achieved with such a configuration. Importantly, the surface wave efficiency across this band of frequencies is high—greater than 85%. It will also be shown that these stacked patches have lower cross-polarization levels compared to a conventional stacked patch and, thus, are very suited to circular polarization applications. Two circular polarization (CP) configurations are presented and experimentally verified. The single- and dual-feed configurations have 3-dB axial ratio bandwidths of 18% and 32%, respectively.**

***Index Terms*—Broad-band antennas, printed antennas.**

I. Introduction

ONE salient feature of the microstrip patch is its ease of integrating with active devices. Printed antennas can be etched/fabricated on the same material used to develop microwave amplifiers and photonic devices, thereby making the transmitter and/or receiver module small in size [1]. Two such problems with this antenna/device integration technique are the excitation of surface waves reducing the antenna efficiency and also the limited achievable bandwidth [2]. Aperture-coupled patches alleviate this problem to an extent, however, these patches can suffer from layer alignment difficulties and the surface wave excitation can still have a detrimental effect on the antenna performance [3].

Several other methods have been proposed to address the problem of printed antenna/active device integration with, however, somewhat limited success [4]–[6]. These techniques are based on the principle that if the patch is large enough, the TM_0 surface wave will not be excited. Such methods can yield enhanced surface wave efficiency; however, these proposals are typically narrow band, which limits their application. Recently, it was shown that by simply stacking the patch etched on the high dielectric constant material with a patch mounted on a low dielectric constant material, in this case foam, the previously encountered problems can be resolved [7]. Bandwidths in excess of 25% were achieved with the surface wave efficiency greater than 85% over this band. It was postulated that the upper patch couples strongly to the typically excited surface, thereby reducing its effect on the overall radiation performance of the antenna.

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The author is with the Department of Communication and Electronic Engineering, RMIT University, Melbourne, VIC 3001 Australia.

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In this paper, we further investigate the performance of the *hi-lo* dielectric constant stacked patches, in particular, focusing on the radiation characteristics of this antenna. It will be shown that these patches yield low cross-polarized fields making this printed antenna very suited to circular polarization (CP) applications. Section II presents the overall performance trends of the *hi–lo* stacked patch, comparing its performance to single-layered and other stacked configurations. Section III presents two simple techniques using the *hi–lo* stacked patch, which result in good CP behavior over the entire impedance bandwidth. These configurations are investigated experimentally and excellent agreement with the predictions was achieved.

II. Properties of *Hi–Lo* Stacked Patches

To thoroughly investigate the performance of *hi–lo* stacked patches, a full wave spectral-domain analysis developed *in house* [8] and *Ensemble 5.1* [9] were utilized. These packages take into account the surface wave effects and accurately model the feed technique incorporated. *Ensemble* has the added feature of allowing multiple dielectric layers, thereby modeling the effect of the thin layer of material used to etch the upper patch and giving more accurate impedance modeling.

Fig. 1 shows the printed antenna configuration. Here an arbitrary shaped patch is etched or grown on a grounded high dielectric constant material. A second patch residing on a layer of low dielectric constant material is parasitically coupled to the driven antenna. The lower patch can be edge or probe fed (here shown as edge fed). As stated in [7], this technique to achieve high surface wave efficiency is independent of the patch conductor shape. Fig. 2 shows the predicted and measured input impedance behavior of a *hi–lo* stacked patch configuration incorporating rectangular patches and a probe feed (refer to the caption of Fig. 2 for the relevant dimensions). The lower layer has a dielectric constant ε_{r1} of 10.4, and a thickness d_1 of 1.905 mm (or 0.032λ_0 at the design frequency of 5.0 GHz). The upper layer is foam [$\varepsilon_{r2} = 1.07$, $d_2 = 4.5$ mm (or 0.075λ_0)]. As can be seen from this plot, good agreement between theory and experiment was achieved. Here the measured and predicted *10-dB return loss* bandwidths are 27% and 26%, respectively. The discrepancy between the measured and calculated impedances at the higher end of the frequency may be due to the inaccuracies associated with the experimental "de-embedding" of the SMA connector used to feed the antenna. A thin dielectric layer (0.254 mm) of *RT/Duriod 5880* was used to etch the top conductor and was taken into account using the *Ensemble 5.1* package. As this

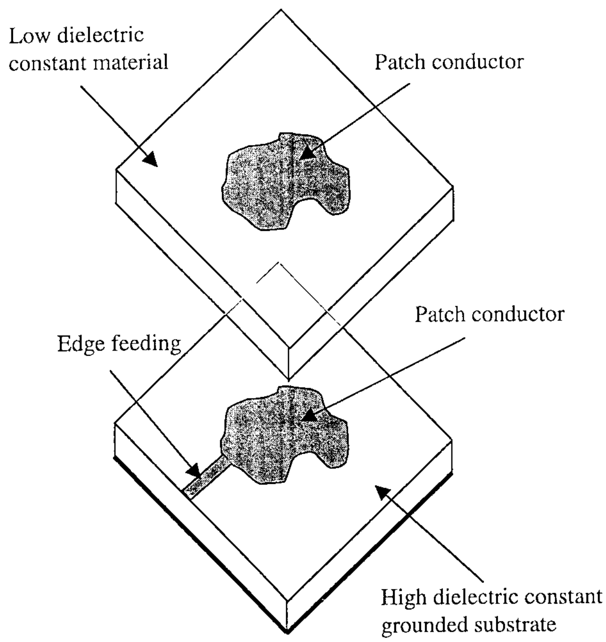


Fig. 1. Schematic of *hi–lo* stacked-patch structure.

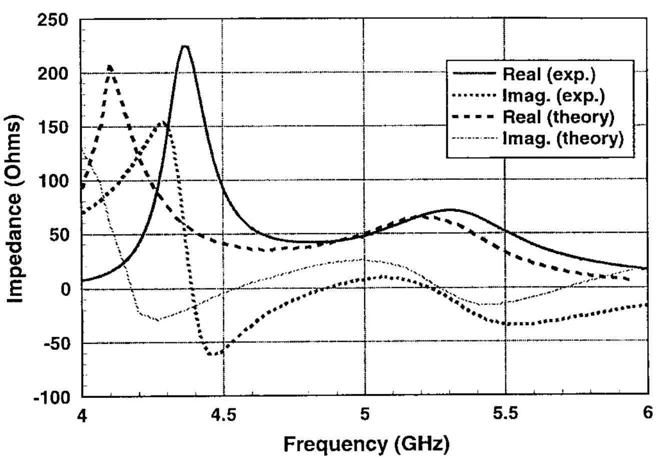


Fig. 2. Input impedance of rectangular *hi–lo* stacked-patch antenna (*parameters*: $\varepsilon_{r1} = 10.4$, $d_1 = 1.925$ mm, tan $\delta_1 = 0.001$, $e_{r2} = 1.07$, $d_2 = 4.5$ mm, tan $\delta_2 = 0.001$, $L_1 = 9.4$ mm, $W_1 = 8.8$ mm, $L_2 = 21.4$ mm, $W_2 = 20.4$ mm, $x_p = 4.3$ mm, $r_0 = 0.325$ mm).

layer is electrically thin, its overall effect on the performance of the antenna is minimal. To put these results into perspective, a single-patch etched on the lower dielectric layer alone has a *10-dB return loss* bandwidth of 1.6%. A single patch using the lower dielectric constant with the same thickness of the *hi–lo* configuration would not be matched to 50 Ω at resonance due to inductive nature of the feed for such a thick substrate (in excess of $0.1\lambda_0$). The measured gain of the *hi–lo* antenna was greater than 6.5 dBi over the 10-dB return loss bandwidth. This value is comparable to a stacked patch incorporating low dielectric constant material combinations [10], inferring that the surface wave efficiency is relatively high.

Fig. 3 shows the calculated surface efficiency [2], [5], [8] η_{sw} of two *hi–lo* configurations as a function of normalized frequency (normalized to the center of the *10-dB return-loss* bandwidth f_c). Each stacked patch uses a lower layer with $\varepsilon_r = 10.4$ and $d = 0.032\lambda_c$ and an upper layer of $\varepsilon_r = 1.07$ and $d = 0.067\lambda_c$ (where λ_c is the wavelength corresponding to f_c). The first configuration consists of a stacked rectangular patch combination and the second is for a stacked annular ring scenario. As for the circular patch case presented in [7], η_{sw} is greater than 85% over the 10-dB return-loss band of frequencies (ring: $0.895f_c$ to $1.105f_c$; rectangular: $0.885f_c$ to $1.115f_c$). Note the peak in efficiency for the rectangular case is approximately 93% and is near the upper edge of the *10-dB return-loss* bandwidth. After this peak, η_{sw} gradually decreases until the two patches no longer strongly couple resulting in the rapid decay of η_{sw}. Eventually, η_{sw} approaches values for the case of a single-layered geometry etched on the high dielectric constant material (see [5]). For the annular ring case note the maximum efficiency is slightly higher than the rectangular patches at the expense of reduced bandwidth where the efficiency is high (above 85%). Indeed the impedance bandwidth of the annular ring configuration is slightly lower too, approximately 21% compared to 23% for the rectangular *hi–lo* case. Thus, there appears to be a tradeoff between maximum surface efficiency and both return loss and η_{sw} bandwidth, as for the case for a conventional stacked patch configuration [10]. Once again to put these results into perspective, a patch etched on the lower dielectric material alone has a surface wave efficiency of 66%. A single patch etched on a thick lower layer (corresponding to the total thickness of the *hi–lo* antenna) has a surface wave efficiency less than 15% due to the excitation of both the TM_{01} and TE_{01} surface wave modes. It is interesting to note that for all the cases considered; including a circular patch *hi–lo* structure [7], the maximum peak in efficiency does not match the lowest return-loss value. This is similar to the cases presented in [5] and [6], although there is a better correlation here.

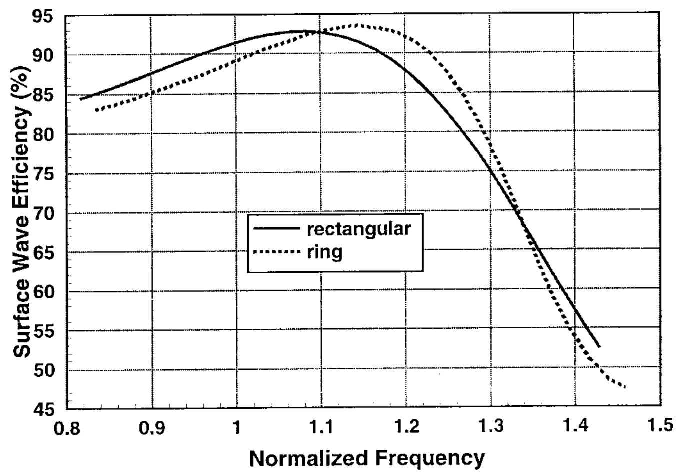


Fig. 3. Surface wave efficiency of *hi–lo* stacked-patch antennas.

As mentioned in [7], the *hi–lo* stacked-patch antenna has low cross-polarized radiation levels. Fig. 4 shows the theoretical H-plane cross-polarized levels for four probe-fed patch configurations: 1) a single-layered circular microstrip

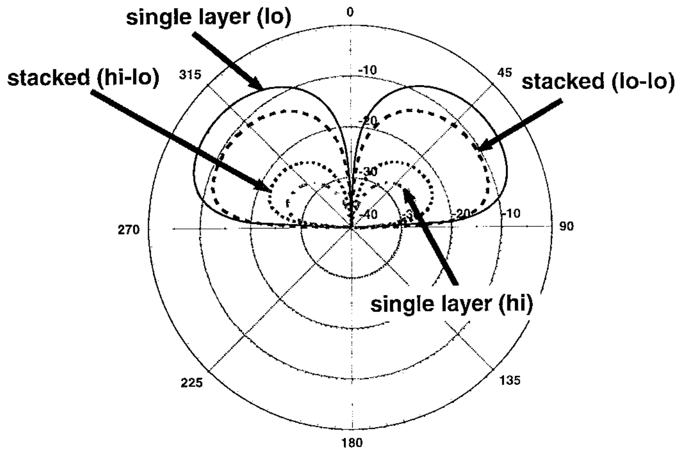


Fig. 4. Cross-polarization levels of several probe-fed patches.

patch antenna mounted on a low dielectric constant material ($\varepsilon_r = 2.2$); 2) a stacked circular microstrip patch configuration utilizing a *lo–lo* combination of materials ($\varepsilon_{r1} = 2.2$ and $\varepsilon_{r2} = 1.07$); 3) a single-layered circular microstrip patch antenna mounted on a high dielectric constant material ($\varepsilon_r = 10.4$); and 4) a stacked circular microstrip patch configuration utilising a *hi–lo* combination of materials ($\varepsilon_{r1} = 10.4$ and $\varepsilon_{r2} = 1.07$). All combinations have been designed for the same center frequency and the thicknesses of lower dielectric layers are also the same ($0.03\lambda_0$). For the stacked cases, the upper dielectric layer has a thickness of $0.06\lambda_0$. From Fig. 4, there are several important findings. Before exploring these, it is important to note that the main source of cross-polarized fields is the discontinuity associated with the feed (here a probe) and the driven patch conductor. This is why direct contact fed patches have greater cross-polarization levels than noncontact printed antennas (such as aperture-coupled patches).

The first trend to observe from Fig. 4 is that the cross-polarized field level for the *lo–lo* stacked patch combination is less than for the single-layered patch utilising a low dielectric constant substrate (here by 5 dB). This observation can be attributed to the presence of the parasitically coupled patch. As there are no discontinuities associated with this second patch and the centers of each patch are aligned as well as the second element being reasonably far from the discontinuity associated with the driven patch and the probe, it can be expected that the cross-polarized radiated power will be lower.

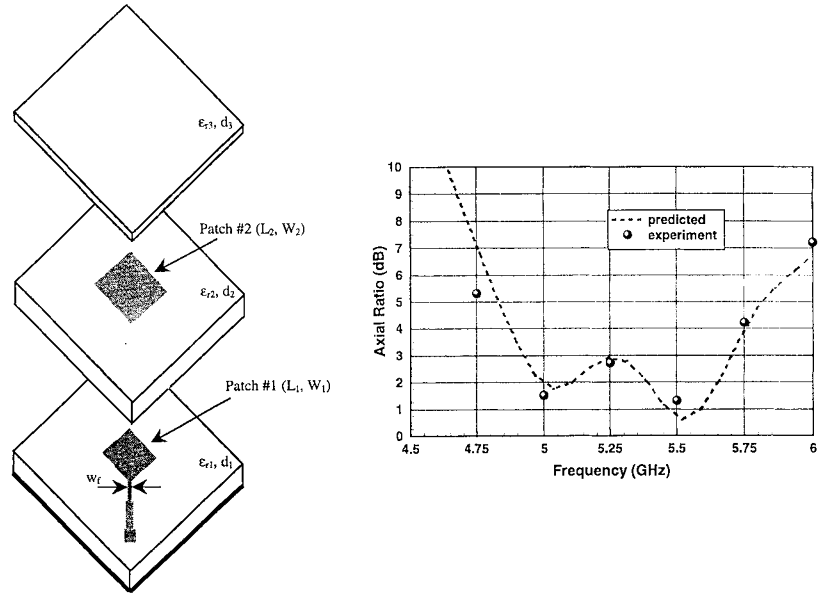
From Fig. 4 it can be seen that the single-layer patch using a high dielectric constant substrate has significantly less cross polarization than the patch with $\varepsilon_r = 2.2$. This is a result of the cross-polar fields being strongly bound to the material [11]. The *hi–lo* stacked patch has slightly higher cross-polarization levels (5 dB) than the single-layer scenario due to the parasitically coupled element drawing power from the lower element. Thus, there is one minor tradeoff of the new configuration—the *hi–lo* patch has far superior η_{sw} and impedance bandwidths compared to the single-layer geometry at the expense of slightly higher cross-polarization levels. It should be noted that the cross polarization of the *hi–lo* stacked patch is significantly lower (15 dB) than the conventional stacked configuration. This makes the *hi–lo* structure a prime candidate for circular-polarization generation, where the cross-polarization level governs the quality of the axial ratio (AR).

III. Circular-Polarization Examples

There are a variety of methods for generating circular polarization from a microstrip patch antenna [2]. One of the simplest means is to use a single-feed arrangement. Here the feed is located in the D-plane ($\phi = 45°$) on an almost square or circular patch to excite two orthogonal modes with a 90° phase difference. The phase shift is achieved by raising the resonant frequency of one mode above the other and operating between the two resonances [12]. This method requires no additional phase shifting element, however, as has been shown in the literature, it is generally narrow band, typically a fraction of the impedance bandwidth [2]. Another problem with the single-feed technique is that the minimum achievable axial ratio is limited by the discontinuity (and, hence, cross-polarization component) associated with the feeding network.

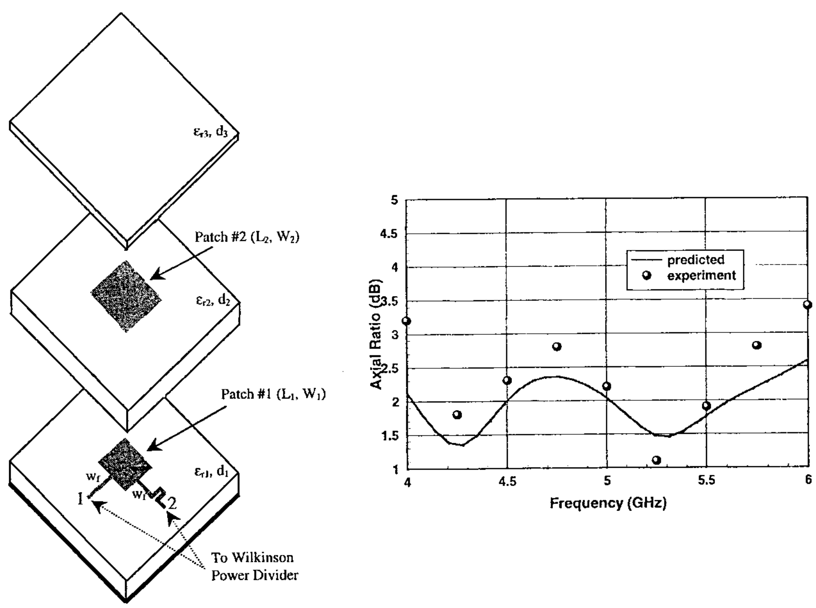
Fig. 5(a) shows an edge-fed *hi–lo* stacked-patch configuration designed to generate circular polarization using the materials described earlier. The dimensions of the patches were optimized to achieve good axial ratio and impedance bandwidth using *Ensemble 5.1* (refer to the Fig. 5 caption for the dimensions). As mentioned in the previous section, since the *hi–lo* stacked-patch configuration generates low levels of cross-polarization, good quality axial ratio should be obtainable. Fig. 5(b) shows the predicted and measured axial ratio of this configuration. The measured *3-dB axial ratio* bandwidth is 18%. Using the appropriate matching structure, a similar *10-dB return-loss* bandwidth was achieved. To the author's knowledge, these results are the largest recorded bandwidths for a single-feed CP microstrip patch structure. The good axial ratio response is a direct consequence of the dielectric layer composition used.

Probably the most common means of obtaining CP from a microstrip patch antenna is to incorporate two orthogonal feeds excited 90° out of phase [2]. Once again, this method has had limited success when using conventional dielectric structures due to the spurious fields radiated from the feed network, in particular when direct contact feeds are used [13]. Fig. 6(a) shows a schematic representation of an edge-fed *hi–lo* stacked-patch version of this CP microstrip antenna. Here the patch is fed by a Wilkinson power divider (refer to [14] for design details). To achieve the 90° phase shift between the two orthogonal feeds, a 90° delay line was incorporated into the microstrip feed network. To model this configuration, *Ensemble 5.1* was utilized, although the Wilkinson power divider was not modeled in the simulation. Fig. 6(b) shows the predicted and measured axial ratio of this configuration. As can be seen from Fig. 6(b), the agreement between experiment and prediction is good, with the measured *3-dB axial ratio* bandwidth is in excess of 32%. The discrepancies between the results can be attributed to simulation assuming an equal magnitude excitation at both ports [1 and 2 in Fig. 6(a)] and a 90° phase shift between these ports across the frequency band.



(a) (b)

Fig. 5. (a) Schematic and (b) axial ratio for single-feed *hi–lo* stacked-patch configuration (*parameters*: $\varepsilon_{r1} = 10.4$, $d_1 = 1.524$ mm, tan $\delta_1 = 0.001$, $e_{r2} = 1.07$, $d_2 = 5.0$ mm, tan $\delta_2 = 0.001$, $\varepsilon_{r3} = 2.2$, $d_1 = 0.254$ mm, tan $\delta_3 = 0.001$, $L_1 = 9.0$ mm, $W_1 = 7.8$ mm, $L_2 = 20.7$ mm, $W_2 = 15.5$ mm, $w_f = 0.25$ mm).



(a) (b)

Fig. 6. (a) Schematic and (b) axial ratio for dual-feed *hi–lo* stacked-patch configuration (*parameters*: $\varepsilon_{r1} = 10.4$, $d_1 = 1.925$ mm, tan $\delta_1 = 0.001$, $e_{r2} = 1.07$, $d_2 = 4.5$ mm, tan $\delta_2 = 0.001$, $\varepsilon_{r3} = 2.2$, $d_1 = 0.254$ mm, tan $\delta_3 = 0.001$, $L_1 = 9.4$ mm, $W_1 = 9.4$ mm, $L_2 = 21.4$ mm, $W_2 = 21.4$ mm, $w_f = 1.766$ mm).

The *10-dB return-loss* bandwidth was of similar order to the axial ratio (AR) bandwidth as a consequence of the resistor (100 Ω) in the power divider.

IV. Conclusions

In this paper, the features of stacked patches incorporating a high dielectric constant layer/low dielectric constant material arrangement have been presented. It has been shown that this printed antenna configuration can have broad impedance bandwidths, in excess of 25% and good surface wave efficiency across this frequency band. It has also been shown that the *hi–lo* stacked patch has low cross-polarization levels and, therefore, is very suited to circular polarization applications. Two CP configurations have been analyzed and presented with very good AR bandwidths.

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Rod Waterhouse (S'89–M'94) received the Bachelor of Electrical Engineering (honors), Masters of Engineering Science (research), and the Ph.D. degrees from the University of Queensland, Australia, in 1987, 1990, and 1994, respectively.

In 1994, he joined the Department of Communication and Electronic Engineering at the RMIT University, Melbourne, Australia, where he is currently a Senior Lecturer. His research interests include printed antennas, phased arrays, design of antennas suitable for mobile communication systems, and optically distributed microwave systems. He has consulted for several companies and institutions including Radio Frequency Systems, British Aerospace, the Australia Telescope National Facility and the Australian Army Engineering Agency in the areas of microwave, RF/photonic, and antenna technologies.

Dr. Waterhouse was awarded a Large Australian Research Council (ARC) Grant (fiber feeder networks for LMDS) in 1999. He has also received ARC funding for projects related to integrated photonic/antenna modules and optical phase shifters. He is the IEEE Microwave Theory and Technique and Antennas and Propagation Chapter Chair for the Victorian Section.