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Investigation Into the Performance of Proximity Coupled Stacked Patches

Wayne S. T. Rowe, *Member, IEEE*, and Rod B. Waterhouse, *Senior Member, IEEE*

***Abstract*—We investigate the parameters that control the impedance and radiation performance of proximity coupled stacked microstrip patch radiators. In particular we explore the relationship required between the dielectric layers to achieve broadband behavior and also how the dimensions of the stacked radiators and the relative location of the feed can influence the impedance response. Bandwidths in excess of 20% can be achieved with careful layer design. We also investigate the dielectric layer configurations required to achieve broadband impedance responses when higher dielectric constant feed material is used. This latter study is of particular importance when designing MMIC compatible printed antennas.**

***Index Terms*—Antenna feeds, microstrip antennas, MMIC, proximity coupling, stacked patch antennas.**

I. INTRODUCTION

IN the mid-to-late 1980s, noncontact feeding techniques for microstrip patch antennas were introduced [1], [2]. Since then these methods, aperture coupling and proximity coupling, have helped overcome several of the performance hindrances associated with direct contact excitation procedures (probe and edge feeding). These include the inherent narrow bandwidth of direct contact fed patches and also the spurious radiation associated with the current discontinuity where the feed and the patch join.

Despite overcoming these detrimental attributes, proximity coupled patches have received little attention in the literature. This may be because the original form [2] required an external impedance matching circuit to achieve a reasonable impedance bandwidth (approximately 13%). To the authors' knowledge there appears to be no overview on how to achieve broad impedance bandwidth responses for printed antennas based on proximity coupled stacked patches, or how varying the parameters of this printed antenna affect the impedance and radiation performance. Such design studies can be found for aperture coupled stacked patches [3], aperture stacked patches [4] and direct contact stacked patches [5]. In [6] a stacked proximity coupled patch was developed that displayed a broad impedance bandwidth of approximately 25%, however this was achieved with the assistance of slots within the patch radiators. There still remains unanswered questions on what are the driving parameters that may lead to a broadband response of this printed antenna and whether these printed radiators require modifications (slots, matching structures) to achieve favorable characteristics.

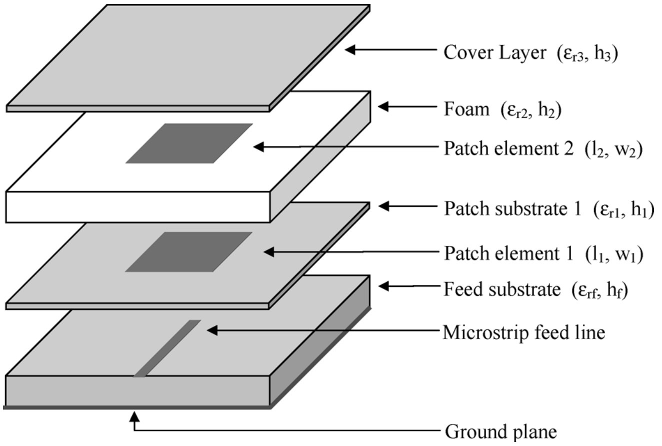

Fig. 1. Stacked proximity coupled patch antenna structure. (Parameters: $l_1 = w_1 = 20$ mm, $l_2 = w_2 = 21.6$ mm, $\varepsilon_{rf} = \varepsilon_{r1} = \varepsilon_{r3} = 2.2$, $\varepsilon_{r2} = 1.07$, $h_f = 1.575$ mm, $h_1 = h_3 = 0.254$ mm, $h_2 = 4$ mm, open circuit offset from patch center $= -3.6$ mm).

In this paper we examine the properties of proximity coupled stacked patches and undertake a parameter study to determine which parameters are most critical in governing the performance of a broadband element. Design trends are presented for all the parameters that affect the impedance and radiation performance of a stacked form of this printed antenna. Recently, we showed experimentally that a simple stacked proximity coupled patch can yield bandwidths of the order of 20% [7] without matching structures or slots. The objective here is to determine what parameters are central to achieving this performance. We also examine the radiation and impedance bandwidth of a proximity coupled patch when the permittivity of the feed and patch substrates are varied, to simulate using this antenna in an MMIC environment. Optimal design configurations and tradeoffs are identified.

II. CHARACTERISTICS OF STACKED PROXIMITY COUPLED ANTENNAS

In [7], we presented a parameter variation study on a conventional proximity coupled patch antenna structure. The results of this study support the initial work undertaken on proximity coupled patches [2], [8]. The bandwidth of proximity coupled patch antennas can be enhanced by stacking an additional parasitic patch over the conventional structure. This configuration is seen in Fig. 1. An antenna of this type was constructed in [7] which had the dimensions quoted in the caption of Fig. 1. This antenna displayed a measured 10 dB return loss bandwidth of

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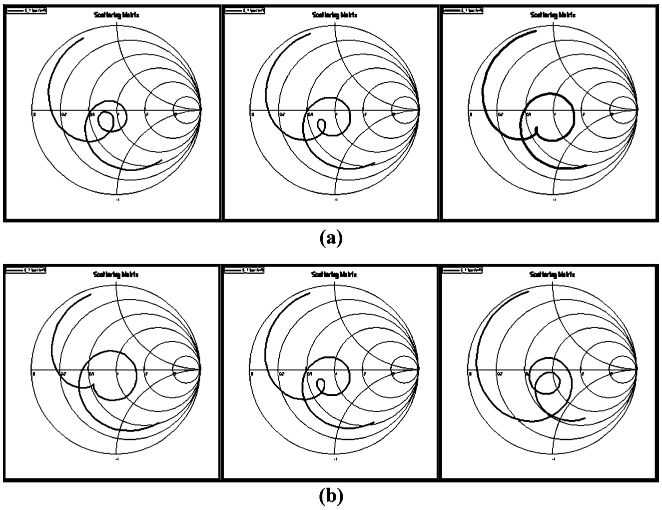


Fig. 2. Stacked proximity coupled antenna patch element variation. (a) Patch element 1 size variation ($l_1 = w_1 = 19.6$ mm, 20 mm, 20.4 mm); (b) patch element 2 size variation ($l_2 = w_2 = 21$ mm, 21.6 mm, 23 mm).

20% and a gain of approximately 9 dBi. To ascertain the design characteristics of the stacked proximity coupled antenna, a parameter study was performed on the architecture in Fig. 1 using the full-wave software package, Ensemble 6.0. Each physical attribute of the antenna was varied independently, whilst holding all others constant. For this study we choose a material selection similar to that used in [4] and [5]. The stacked proximity coupled antenna presented in [7] was used as a baseline.

The parasitic patch elements of the baseline antenna are square. Preserving square patch elements is advantageous as it enables the formation of a dual polarized stacked proximity coupled patch antenna simply with the addition of a second orthogonal feed line. Circular polarization can also be obtained by driving these two feed lines at quadrature. The ensuing parameter study maintains the square geometry of the patch elements, but varies the overall size. Throughout this parameter study, the baseline response is located in the center of each figure (for comparison) with variation below and above the baseline parameter value on the left and right, respectively. All other dimensions except the parameter being varied are kept constant with the baseline antenna. The input impedance is calculated at the end of the 50 Ω microstrip feed line, located 20 mm from the center of the patch elements.

Fig. 2(a) displays the effect on the input impedance when both the length (l_1) and the width (w_1) of the lower patch element are altered by 0.8 mm $(\sim 0.013\ \lambda_0)$. The variation of patch element 1 affects the level of mutual coupling between the two patches, which can be observed as a change in size of the small inner loop in the impedance loci of Fig. 2(a). An increase in patch size corresponds to a reduction in the magnitude of mutual coupling. The larger outer loop is a manifestation of the coupling from the open circuit microstrip feed line to the patch elements, which is also altered when changes are made to the size of patch element 1. As patch element 1 is physically located in the middle of the antenna, it is understandable that variation of this element will influence both coupling levels. Patch element 2 is situated close to the top of the antenna structure, and primarily influences the interaction between the two patches, as can be seen in Fig. 2(b). It should be noted that an increase in the size (l_2 and w_2) of patch element 2 has the converse effect to patch element 1 on the magnitude of mutual coupling between the two patches. This emphasizes that the relative size of the two patch elements influences the mutual coupling between them, rather than the absolute size of each patch. The effect on the overall input impedance response is less sensitive to changes in the size of patch element 2 than patch element 1. The change in patch element 2 dimensions shown here is 2 mm $(\sim 0.033\ \lambda_0)$.

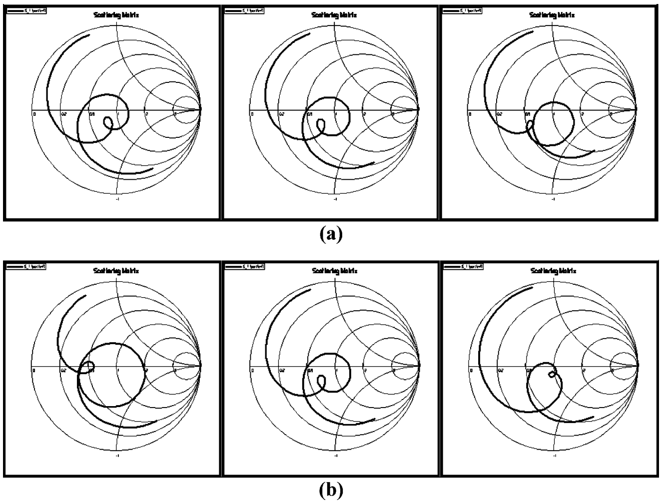
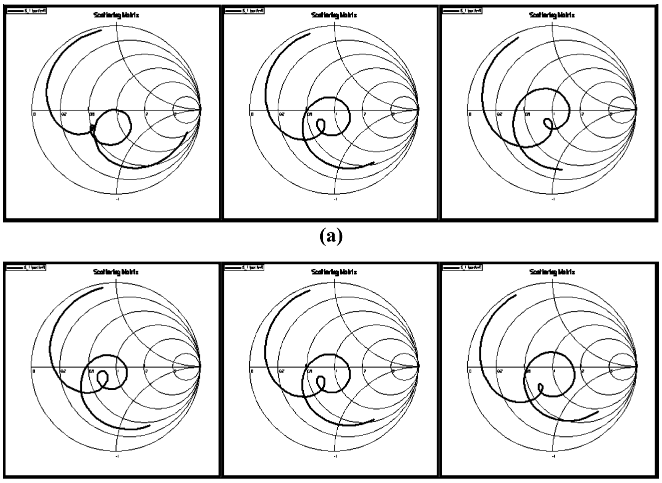


Fig. 3. Stacked proximity coupled antenna substrate variation. (a) Patch substrate 1 thickness variation ($h_1 = 0.127$ mm, 0.254 mm, 0.508 mm) and (b) foam thickness variation ($h_2 = 3$ mm, 4 mm, 5 mm).

The input impedance plots in Fig. 3(a) depict the consequence of varying the height of patch substrate 1. Typical substrate heights for *RT/Duriod 5880* were used in this case study. As this substrate is situated between the feed line and the lower patch element, a change in the coupling characteristics from feed to patches is predicted to be the primary consequence. This is evident in Fig. 3(a), although the values of substrate height remain relatively small ($\sim$ 0.0021 to 0.0085 λ_0), so strong coupling is still observed for all cases. For the foam substrate variation in Fig. 3(b), an increase in height diminishes the magnitude of mutual coupling between the patches. However, the feed to patch coupling is also reduced. This could be due to the feed to patch coupling being governed by the characteristics of the mutually coupled patches as a single entity, and disturbing this will therefore transform the way the feed and patches interact. Once again typical commercially available foam thicknesses were used in this study.

Feed substrate height variation predominantly induces a change in the level of coupling between the feed and patch elements, as evident in Fig. 4(a). This effect is analogous to the conventional single layer proximity coupled patch antenna case. The microstrip feed line width was adjusted with the alteration of the feed substrate height to maintain a 50 Ω characteristic impedance. The stub offset is defined as the distance of the microstrip feed line open circuit from directly underneath the geometric center of the patch element. Modifying the stub


(a)

(b)

Fig. 4. Stacked proximity coupled antenna feed parameter variation. (a) Feed substrate thickness variation ($h_f = 1.016$ mm, 1.575 mm, 2.083 mm) and (b) stub offset variation (-2 mm, -3.6 mm, -5.2 mm).

offset position had minimal consequence on the impedance response of the stacked proximity coupled antenna, unless large alterations were considered (e.g., $> 0.02\ \lambda_0$). The effect of large variations in the stub offset position can be seen in Fig. 4(b). This fact can be valuable if a dual or circularly polarized proximity coupled antenna is desired. If a second orthogonal feed line is added to the structure to obtain a dual or circularly polarized antenna (as stated previously), the open circuit terminations on the end of the microstrip feed lines can be moved away from the center of the antenna without greatly affecting the impedance response. This assists in decoupling the feed lines and improves the isolation between them.

The majority of the parameter variations in this study had only a minor influence on the gain of the antenna. Typically, the gain varied less than 0.2 dB from that of the baseline antenna. As for the single layer proximity coupled patch antenna case the exception was the feed substrate height, where the gain showed the most significant rise when the substrate thickness was increased.

As the stacked proximity coupled patch antenna is a multi-resonant structure, there are numerous interactions that influence the response. The dominant performance trends have been identified via a parameter study. These can be summarized as follows: The mutual coupling of the two patch resonances primarily corresponds to a loop in the input impedance locus (for this case it is the small inner loop); the second (large outer) loop relates to the interaction between the microstrip feed line and the resonantly coupled patch elements. Thus, a good starting point to achieve a broadband impedance response is to use a stacked structure (similar to Fig. 1) with an electrically thick feed substrate to encourage higher gain. However, the feed substrate should not be excessively thick, as this would promote surface wave generation. A good guide is a thickness of around $0.025\ \lambda_0$. To ensure sufficient coupling to the patch elements, a thin substrate layer between the microstrip line and patch element 1 is required. The trends observed in the parameter study may then be employed to optimize the stacked proximity coupled antenna.

III. EFFECT OF SUBSTRATE LAYER PERMITTIVITY IN A STACKED PROXIMITY COUPLED PATCH ANTENNA

As with any stacked patch antenna configuration, there are several degrees of freedom in the design of these elements, however as was shown in [9] for a direct contact stacked patch, the dielectric layers govern the overall performance of the antenna. In this section we are going to investigate the composition of the dielectric layers to achieve good impedance responses and also whether the postulation in [10] holds, namely for broadband stacked patches the dielectric constant of the layer below patch element 1 should be the same as that of the feed layer. Thus the trends we are going to explore here are: the relationship between the dielectric constant of the feed layer and the bandwidth of the printed antenna; whether ε_{r1} needs to be high if ε_{rf} is high; and for the case when ε_{rf} is low is there any advantage in not having ε_{r1} the same as ε_{rf}. Before launching into these investigations a comment should be made on the permittivity of the material below patch element 2, namely, ε_{r2} in Fig. 1. As has been shown for all stacked patch configurations, independent of the feeding technique, the dielectric constant of this material needs to be as close to unity as possible. The reason for this, as was given in [9], is to ensure the antenna efficiency is as high as possible.

A. The Relationship of ε_{rf} and ε_{r1} to the Bandwidth and Gain

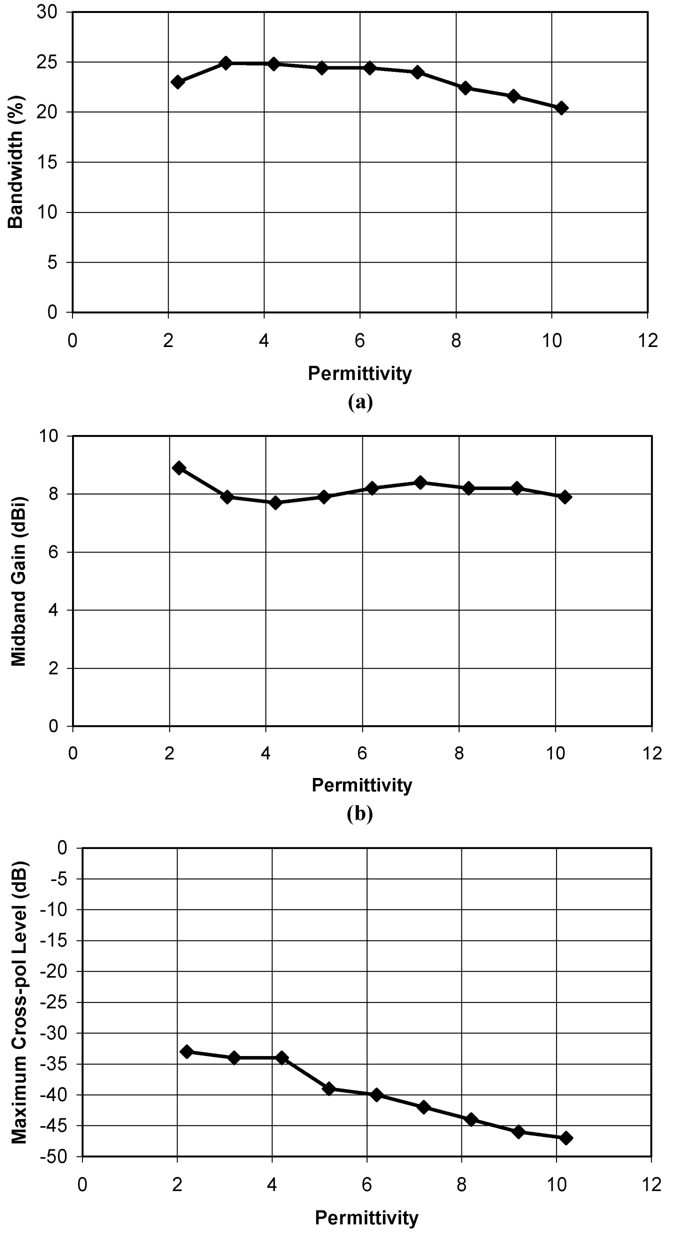
In Fig. 5, the characteristics of a stacked proximity coupled patch antenna are tracked as the permittivity of both the feed substrate and patch substrate 1 are incremented, so that they retain the same value. The microstrip feed line width is altered at each step, to maintain a 50 Ω characteristic impedance. The structure was then optimized for maximum impedance bandwidth. Fig. 5(a) displays the impedance bandwidth as a function of the permittivity of the feed and patch substrates. Interestingly, the maximum bandwidth was not achieved using the lowest permittivity value of 2.2. This may be due to the use of commercially available substrate thicknesses of this material for this particular configuration, which is not necessarily the case for the antennas with a higher permittivity. The bandwidth remains relatively constant for permittivity values between 3 and 7, and then begins to reduce in the region from 7 to 10. For all of the permittivity values analyzed, the bandwidth remained in excess of 20%.

The center frequency gain for the stacked proximity patch antenna versus the feed and patch substrate permittivity is depicted in Fig. 5(b). The maximum gain of 8.9 dBi was registered for the case when both the feed substrate and patch substrate 1 has a dielectric constant of 2.2. The gain remained high as the two substrate permittivities were sequentially incremented, oscillating around a value of 8 dBi. Gain variations across the impedance bandwidth are typically in the range of 1 to 1.5 dB.

As previously stated, the proximity coupled patch structure inherently quells spurious feed radiation by avoiding the current discontinuity associated with contacting feed methods. This results in proximity coupled patch architectures exhibiting very

Table I
RELATIONSHIP BETWEEN ε_{r1} AND BANDWIDTH WHEN ε_{rf} IS HIGH

ε_{r1}	10.4	8.8	6.8	4.5	2.2
2:1 VSWR bandwidth (%)	23.7	25.6	26.2	21.4	22.0
Gain (dBi)	8.1	8.0	8.0	8.2	8.3



(a)

(b)

(c)

Fig. 5. Result of varying the feed and patch substrate permittivity simultaneously on (a) bandwidth, (b) gain at the center frequency and (c) maximum cross-polarization level.

low levels of cross-polarization. Fig. 5(c) plots the maximum level of cross-polarized radiation (with respect to the broadside co-polarized level) in the forward hemisphere of the stacked proximity coupled patch antenna verses the feed and patch substrate permittivity. The cross-polarization level decreases steadily with an increase in the permittivity. A 14 dB difference is observed between the permittivity values of 2.2 and 10.2. It should be noted that the simulation software Ensemble 6.0 employs a method of moments solution, assuming and infinite ground plane and lateral substrate extents. Hence the absolute values of the cross-polarization levels are lower than practically possible.

An antenna that combines the stacked proximity coupled patch architecture with a high dielectric constant feed substrate was constructed and is presented in [10]. By using a second high dielectric laminate as patch substrate 1, this antenna produces a 10 dB return loss bandwidth of 21%, and a gain of 8 dBi. This configuration is a very promising candidate for integration with MMIC devices. The key to achieving such a performance is to use a thin layer of the same (or similar) high dielectric constant material between the feed layer and the first patch.

B. Broadband, Efficient Proximity Coupled Stacked Patches Mounted on High Dielectric Constant Material

This investigation is directly related to the results presented in [10]. It was shown that good bandwidth and efficient radiation could be achieved for the case of a proximity coupled stacked patch mounted on a high feed dielectric constant if the next layer was of similar dielectric constant value. This is pertinent for directly mounting broadband patches on MMIC material as the first patch element does not need to be grown directly on the MMIC material to achieve broadband, efficient performance (as was necessary in [11]). This results in only a small footprint on the MMIC substrate. However, expensive wafers are still required to ensure the dielectric constants of the feed layer and first patch layer match. In this section, we theoretically investigate whether a different dielectric constant material can be substituted for the high dielectric constant first layer and thereby reducing the cost of the directly integrated patch antenna.

The results in [10] are used as a baseline case. For this configuration, we reduced the dielectric constant of patch substrate 1 by decrements of approximately 2 and then optimized the other parameters to ensure the best performance was achieved. Table I summarizes the results the bandwidth and gain results. Interestingly, for ε_{r1} values greater than 4.5, the bandwidth and gain remained approximately the same and the dimensions of the patches, the thickness of all the materials and the feed location did not have to be changed to optimize the performance. These results are particularly important for integrating proximity coupled stacked patches with MMIC devices. This shows that the first layer does not need to be matched exactly to the feed substrate and therefore a more cost effective material (such as *RT/Duroid 6010* with $\varepsilon_r = 10.4$) can be used for the first layer. As long as there is not a dramatic difference between ε_{rf} and ε_{r1} broad bandwidths should still be achievable. The impedance response of the proximity coupled stacked patch starts to degrade for ε_{r1} values less than or equal to 4.5, when all the other parameters have been fixed to those given in [10]. The reason for this

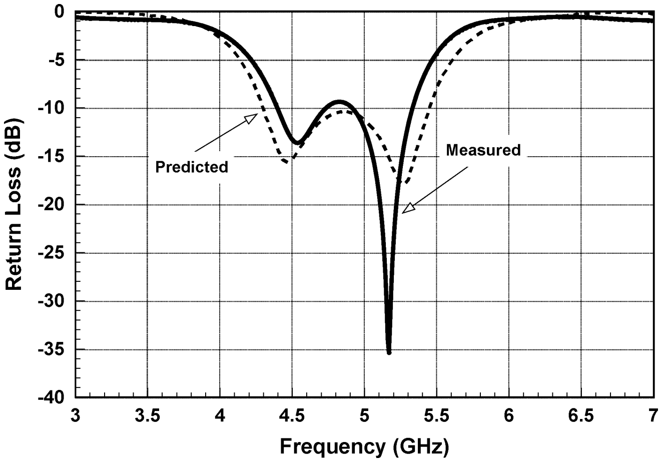
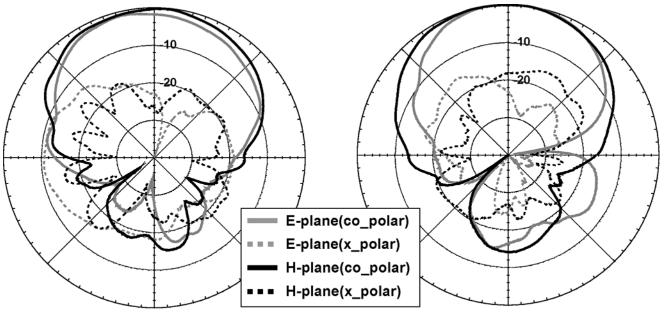


Fig. 6. Return loss performance a proximity coupled stacked patch antenna with a mid-range permittivity for ε_{r1}. (Parameters: $l_1 = w_1 = 9.4$ mm, $l_2 = w_2 = 21$ mm, $\varepsilon_{rf} = 10.2$, $d_f = 1.925$ mm, $\varepsilon_{r1} = 6.15$, $d_1 = 0.254$ mm, $\varepsilon_{r2} = 1.07$, $d_3 = 5$ mm, $\varepsilon_{r3} = 2.2$, $d_4 = 0.254$ mm, open circuit offset from patch center $= -1.5$ mm, ground plane and substrate size $= 40$ mm $\times$ 40 mm).



(a) (b)

Fig. 7. Measured radiation patterns of the antenna at (a) 4.4 GHz and (b) 5.3 GHz.

is that as ε_{r1} is decreased, less of the fields are coupling from the feed line to the first patch as the high dielectric constant feed material confines most of the energy. To resolve this, the thickness of the first layer can be reduced. The bandwidths and gains shown in Table I for $\varepsilon_{r1} = 4.5$ are for when the thickness of this layer has been halved to 0.125 mm. For $\varepsilon_{r1} = 2.2$, an ultra thin layer (0.05 mm) is required to give the results in Table I. This thickness of *RT/Duroid 5880* $(\varepsilon_{r1} = 2.2)$ is not commercially available and is impractical for most applications.

To validate the simulation results an antenna with the configuration shown in Fig. 1 that utilizes a mid-range permittivity for patch substrate 1 was fabricated and tested [12]. The material selection was limited to commercially available microwave laminates. Rogers RO3006 was chosen, which has a permittivity of 6.15 and a thickness of 0.254 mm. Fig. 6 shows the predicted and measured return loss performance of this proximity coupled stacked patch antenna. The parameters for this antenna are given in the caption of Fig. 6. The antenna displays a measured $\mathrm{VSWR} < 2$ impedance bandwidth $(\mathrm{Return\ Loss} < -9.4\ \mathrm{dB})$ of approximately 20%, which is consistent with the radiator presented in [10]. These proximity coupled antenna structures are very sensitive to slight air gaps between dielectric substrates, and this may account for the slight discrepancy between the theory and experimental results.

The co-polar and cross-polar radiation patterns were measured in the E-plane and H-plane across the impedance bandwidth. Fig. 7 shows the radiation patterns at 4.4 GHz and 5.3 GHz. These patterns are consistent with those presented in [10], and also with other previously investigated efficient MMIC-compatible printed antennas. The cross-polar levels in both planes are generally lower than -20 dB at 4.4 GHz, and -15 dB at 5.3 GHz. These levels were slightly higher than predicted, however the theoretical analysis does not account for the finite sized ground-planes/laminates, or the 4-hole flange SMA connector in close proximity to the antenna. The measured gain showed an increase from 6.3 to 7.3 dBi across the impedance bandwidth. This level of gain is also consistent with the antenna presented in [10], and is slightly lower than the predicted gain of 6.8 to 8.7 dBi. This is due to the impact of the small ground-plane not being accounted for in the theoretical model, and the associated increase in cross-polarization levels and backward directed radiation.

C. Proximity Coupled Stacked Patches Mounted on a Low Dielectric Constant Feed Substrate

One of the interesting findings from the previous sub-section is that as the dielectric constant of the first layer is decreased, the thickness of the material must also decrease to achieve good impedance bandwidth. It is worth investigating whether we can use this relationship to remove some of the design restrictions for a proximity coupled stacked patch mounted on low dielectric constant materials.

For this study, we used the proximity coupled stacked patch in [7] as our baseline case. The materials used were a combination of *RT/Duriod 5880* $(\varepsilon_r = 2.2)$ and foam $(\varepsilon_r = 1.07)$ with the feed substrate and patch substrate 1 utilizing the *RT/Duroid 5880*. The thickness of patch substrate 1 was 0.254 mm and a feed offset (from the center of the patch) of 3.6 mm was used to achieve the broadband impedance response. The value of ε_{r1} was increased to 3.5, and then 4.5, and for each case the other parameters of this printed antenna were varied to maintain the original bandwidth. Two important consequences of increasing ε_{r1} were observed. Firstly, to achieve the original bandwidth, we needed to increase the thickness of patch substrate 1 (to 0.508 mm). It also was not necessary to offset the feed line from the center of the patch. Thus using a higher dielectric constant material for patch substrate 1 to a certain extent removes the restriction of requiring a very thin layer between the feed line and the first patch. It also allows for maximum coupling between the feed and the patch and therefore an increased gain. For the three cases considered, the gains were 8.9 dBi $(\varepsilon_{r1} = 2.2)$, 9.2 dBi $(\varepsilon_{r1} = 3.5)$ and 9.3 dBi $(\varepsilon_{r1} = 4.5)$.

IV. CONCLUSION

Proximity coupled stacked patches have been thoroughly investigated in this paper. In particular we have examined the effects of parameter variations on the impedance bandwidth and gain response of these radiators. We have shown that bandwidths of approximately 20% can be achieved for these printed antennas without the addition of matching circuits or slots. For this bandwidth, a stacked structure with an electrically thick feed layer and a thin substrate layer between the microstrip line and the first patch should be used. We have also explored the relationship between achieving broadband impedance behavior and the permittivity values of the materials used to construct the stacked patch antenna. We have shown that impedance bandwidths greater than 20% can be achieved independent of the dielectric constant of the feed substrate, if the layer directly above it is optimized. Simple techniques were devised to ease the thickness restrictions on the dielectric layer between the feed substrate and the first element. These investigations have led to an inexpensive means of developing a wide bandwidth MMIC compatible proximity coupled stacked patch.

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