Design of Wide-Band Aperture-Stacked Patch Microstrip Antennas

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***Abstract*— A variation of the aperture-coupled stacked patch microstrip antenna is presented, which greatly enhances its bandwidth. Bandwidths of up to one octave have been achieved. The impedance behavior of this antenna is compared with that of other wide-band microstrip radiators. Matching techniques for the antenna are presented and their relative merits discussed. The effects of varying several key physical parameters of the antenna are investigated, lending some insight into its wide-band operation. Variations on the design such as incorporation of additional patches are also discussed.**

***Index Terms*— Microstrip antennas.**

I. Introduction

MICROSTRIP patches are an attractive type of antenna due to their low cost, conformability, and ease of manufacture. The aperture-coupled configuration [1] also provides the advantage of isolating spurious feed radiation by use of a common ground plane. However, the primary barrier to implementing these antennas in many applications is their limited bandwidth—only on the order of a few percent for a typical patch radiator. Because of this fact, much work has been devoted to increasing the bandwidth of microstrip antennas. A technique that has been used extensively is stacked patches in which a parasitic element is placed above a lower patch [2], [3]. In this manner, bandwidths on the order of 30–35% can be achieved [4]. Other bandwidth enhancement techniques such as the use of a near-resonant aperture with a thick antenna substrate [5]–[8] are capable of similar performance.

In this paper, we present a microstrip antenna which utilizes a resonant aperture with stacked patches and the result is the near doubling of the achievable bandwidth. The geometry of this aperture-stacked patch (ASP) microstrip antenna is shown in Fig. 1 and differs from the typical aperture-coupled stacked patch antenna in that a larger aperture and thicker substrates are used. Also, the geometry allows for a general multilayered configuration having N dielectric layers with the lower patch being placed directly above layer N_1 and the upper patch directly above layer N_2. The term "aperture coupled" could be used to describe this antenna, however, it is avoided in this text because the aperture is used primarily as a resonator and not as a mechanism for coupling the patches to the microstrip feedline. From this enhanced bandwidth configuration, bandwidths (defined as having a VSWR $< 2:1$) from 50 to 70% have been realized. To the authors' knowledge, this is the widest instantaneous bandwidth yet achieved for a microstrip antenna. Section II provides a comparison of different methods for bandwidth enhancement. Techniques for impedance matching are presented in Section III. The impedance behavior is very sensitive to several physical parameters of the antenna, and the effect of varying these parameters is analyzed in Section IV. Variations on the design such as incorporation of additional patches are discussed in Section V. Finally, details of an experimental design are presented in Section VI.

Manuscript received February 24, 1997; revised April 22, 1998.

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Publisher Item Identifier S 0018-926X(98)06867-7.

II. Comparison of Wide-Band Aperture-Coupled Microstrip Antennas

Both bandwidth enhancement techniques mentioned in the introduction using aperture coupled patches share a common trait—the wide-band characteristics are the result of coupled resonances. The term "mutual resonance" is used here to describe the action of these coupled resonances, which, in general, produces a loop in the impedance locus when plotted on a Smith chart. The operation of each configuration is essentially the same—a resonance which is overcoupled to the microstrip feedline is combined with a low-Q resonance and the results are impedance loci such as those in Fig. 2. In this section, theoretical results from examples utilizing these techniques are compared to those of the ASP antenna; in all three examples the antenna substrates are comprised entirely of foam ($\varepsilon_r = 1.07$). The theoretical analysis is based on the spectral-domain integral equation technique with boundary conditions enforced using a Galerkin moment method (refer to [4], [9]–[11] for more details).

Fig. 2(a) shows the impedance locus of a wide-band microstrip patch using a thick foam substrate and near-resonant aperture. In this case, the overcoupled resonance is that of the aperture and the low-Q resonance is that of the patch. The coupled action of these two resonances produces an impedance locus which exhibits a tight loop around the center of the Smith chart, resulting in a $1.5:1$ voltage standing wave ratio (VSWR) bandwidth of 21% for this example. The advantage of this technique is simplicity of design since only a single patch is used, however, the drawback is the level of back radiation that results from using a large aperture. The front-to-back ratio was better than 12 dB over the band.

At the expense of increased design complexity, back radiation levels may be reduced through the use of stacked patches.

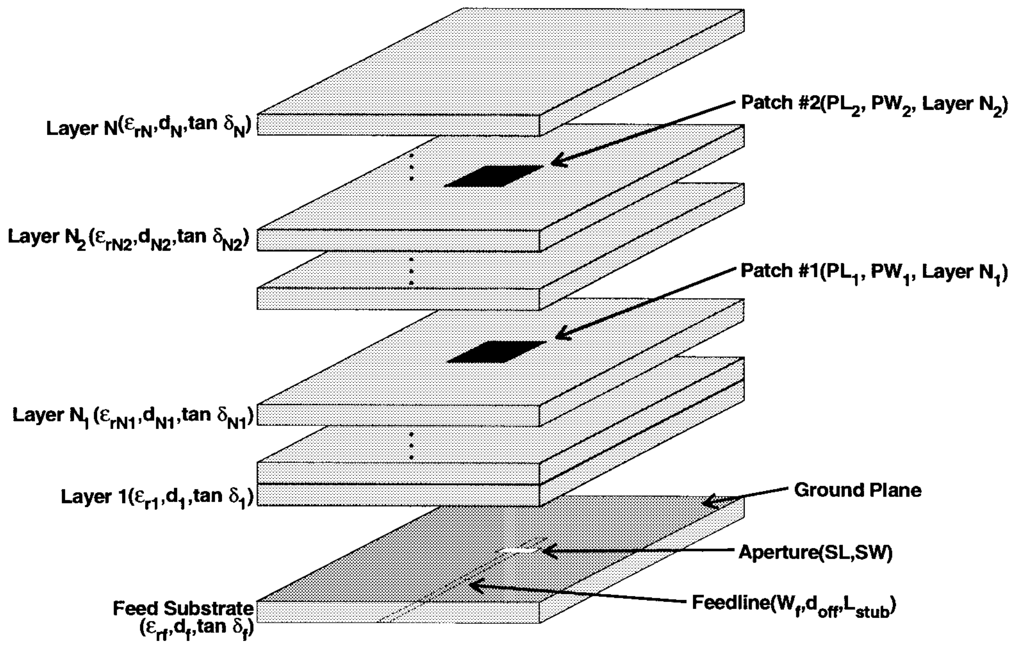
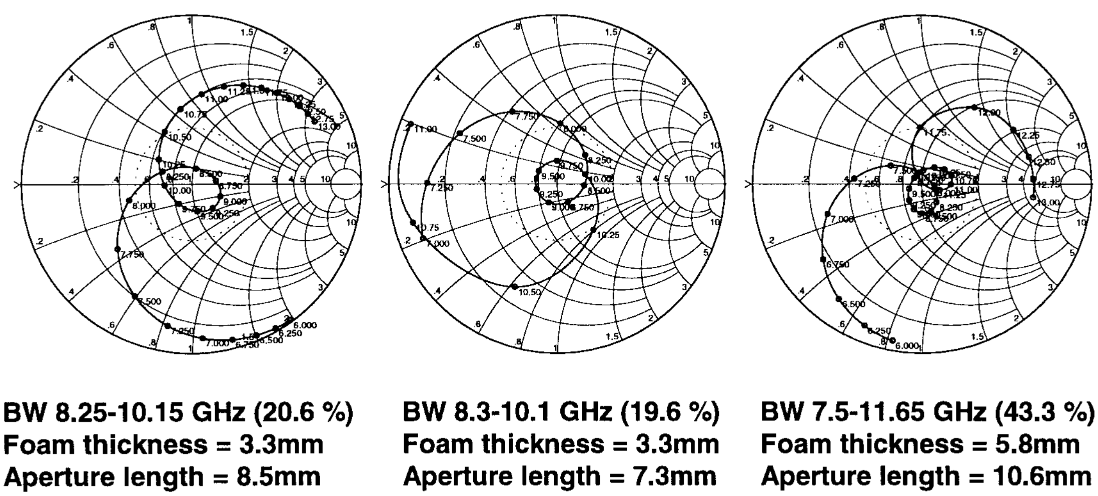


Fig. 1. Geometry of a multilayered ASP antenna.

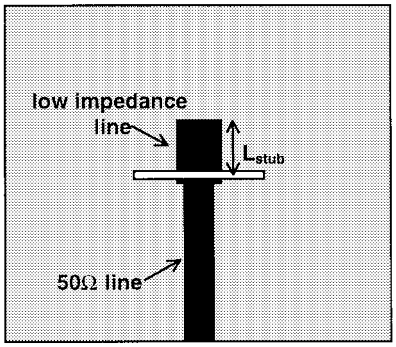


(a) (b) (c)

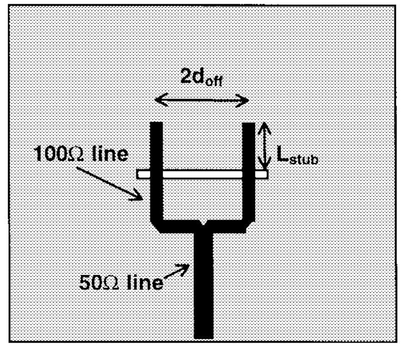
Fig. 2. Impedance loci of wide-band aperture coupled microstrip antennas. (a) Broad-band patch using thick substrate and near-resonant aperture. (b) Aperture-coupled stacked patch. (c) The ASP antenna.

The impedance locus for a typical aperture-coupled stacked patch design is shown in Fig. 2(b). Here, the overcoupled resonance of the lower patch is combined with a low-Q mutual resonance between the patches, and an impedance locus similar to that of Fig. 2(a) results. The antenna substrates consist of foam with a total thickness equal to that of the previous example. A 1.5 : 1 VSWR bandwidth of 20% is achieved and the front-to-back ratio is improved to better than 18 dB over the band.

The use of a resonant aperture with stacked patches results in the ASP antenna with a typical impedance locus shown in Fig. 2(c). This locus differs from those of Fig. 2(a) and (b) with two tight loops near the center of the Smith chart. The locus is produced by the interaction of the individual resonances—a low-Q mutual resonance produced by the interaction of the two patches and a mutual resonance produced by the interaction of the aperture with the lower patch. The latter resonance is overcoupled in the sense that the interaction between the aperture and patch is strong. In the absence of the upper patch, the impedance locus resulting from this overcoupled resonance is similar to Fig. 2(a), however, exhibiting a larger loop that typically cannot be matched to a VSWR $< 2:1$. The mutual resonance between the aperture and lower patch is associated with the lower frequency loop in the impedance locus and the mutual resonance of the two patches produces the upper frequency loop. These mutual resonances can also couple to each other, changing the overall behavior of the impedance locus. The addition of another mutual resonance results in a dramatic increase in bandwidth compared to the previous two configurations, with a 1.5 : 1 VSWR bandwidth



(a)



(b)

Fig. 3. Impedance matching techniques for the ASP antenna. (a) Wide-centered feedline. (b) Dual-offset feedlines.

of 44% being achieved. The required antenna substrate thickness and aperture size are also increased and this, in turn, produces higher back radiation levels with a front-to-back ratio of better than 10 dB over the band for this example.

It was previously speculated that this type of wide-band performance could not be achieved on foam substrates [12]. Although it was achieved in this example, it is generally much more difficult to obtain than if using substrates with higher permittivity. The use of only foam substrates provides a significant improvement in surface wave efficiency. However, there exists a tradeoff of reduced bandwidth—contrary to what is usually observed in a single layer geometry.

III. Impedance-Matching Techniques

In the aperture-coupled microstrip antenna, the most common method of controlling the coupling to the microstrip feedline is to vary the size of the aperture. However, due to the fact that the aperture is used as a radiator in the ASP microstrip antenna, its size cannot be varied independently and the coupling to the feedline must be controlled in another manner. Two techniques to achieve this are shown in Fig. 3.

Use of a radiating aperture results in a high level of coupling, which must be reduced to properly impedance match the antenna. The wide-centered feedline of Fig. 3(a) achieves this through the fact that the coupling decreases with feedline width. This technique is advantageous in its simplicity, however, it generally requires the modeling of currents on the feedline, resulting in a complex analysis. As an alternative, dual-offset feedlines, shown in Fig. 3(b), can be used. In this configuration, the impedance delivered to each feedline at the aperture is nominally 100 Ω. The feedlines ($Z_o = 100$ Ω) are joined by a reactive power combiner. This configuration does not suffer from the increased cross polarization introduced by a single offset feedline and is easily analyzed with a slight modification to the reciprocity method of [10]. Of course, if the area occupied by the feed network is not an issue, a multisection matching transformer can be incorporated in the design.

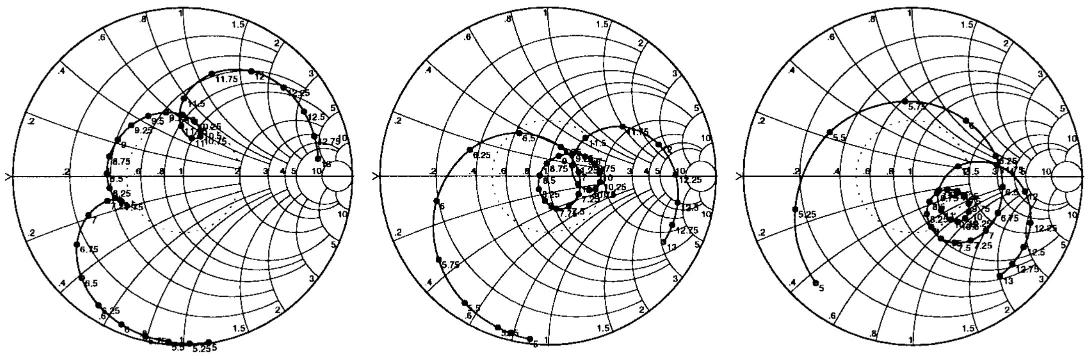
IV. Parameter Study

The complicated operation of the mutual resonances in the ASP antenna introduces a great deal of complexity in the design process. Not only must the coupling between the individual resonators be weak enough to produce tight loops in the impedance locus, but these loops must also be close together in the locus so that they can be matched to an acceptable return loss specification. The best way to gain insight in how to achieve this is through varying several critical physical parameters of the antenna and to note the overall effect on the impedance locus. In this section, we will examine an ASP antenna with two substrate layers and square patches and look at the effect of varying the size of each patch, the aperture length, and the thickness of each substrate layer. Attention will be focused on the size of the loops and their relative position to each other in the impedance locus rather than on impedance matching. Impedance matching can be accomplished by the techniques given in Section III and is independent of the parameters under observation.

The dimensions of the prototype design are given in Fig. 4 and, in each of the examples to follow, all parameters except for one are held constant to the values given. To have an extremely rigorous theoretical model, the currents on the feedline should be modeled for this wide feedline case. However, the model chosen to generate the data was based on the reciprocity method, as it is acceptable to show the trends as the individual parameters are varied while being computationally efficient.

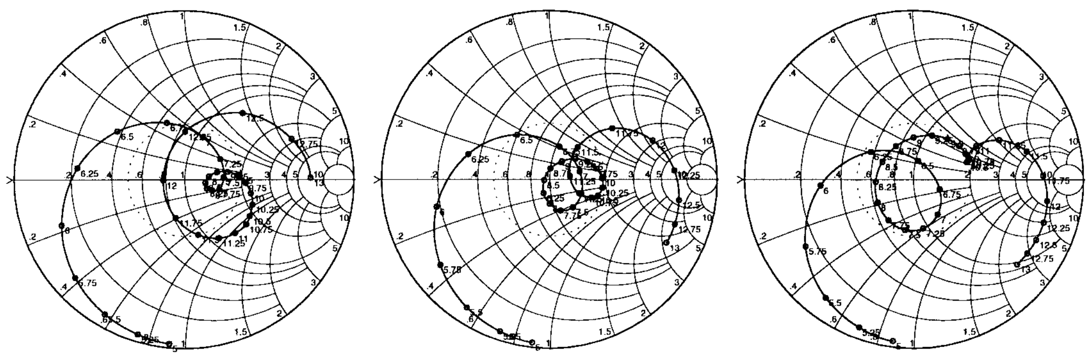
Fig. 4 shows the effect of varying the aperture length on the input impedance locus. It is seen that this has a pronounced effect on the lower frequency loop while having a minor effect on the other loop. This observation supports the previous statement that one loop is due to the interaction of the aperture and lower patch, while the second is due mainly to the interaction of the two patches. Lengthening the aperture has the effect of increasing the coupling between the aperture and lower patch (therefore, increasing the size of the lower frequency loop), while at the same time bringing the two loops closer together.

The effect of altering the size of the lower patch is shown in Fig. 5. This is a critical parameter as the action of the lower patch contributes to both mutual resonances, and, therefore, varying its dimensions has an effect on both loops in the impedance locus. It is very interesting to compare the plots of Fig. 5 with those of Fig. 6, which shows the effect of



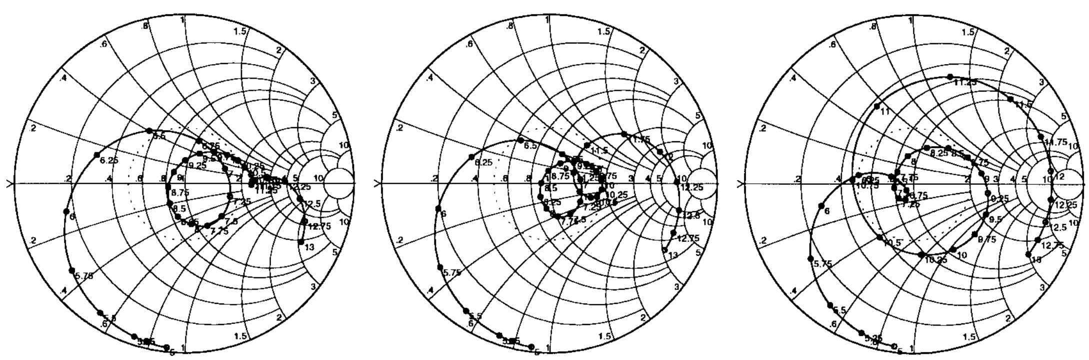
(a) (b) (c)

Fig. 4. Input impedance as a function of aperture length. (a) $SL = 8$ mm. (b) $SL = 10$ mm. (c) $SL = 12$ mm. Other parameters: $W_f = 4.75$ mm, $L_{stub} = 3.4$ mm, $SW = 0.8$ mm. Patches: $PL_1 = PW_1 = 9.1$ mm, $N_1 = 1$, $PL_2 = PW_2 = 10$ mm, $N_2 = 2$. Dielectric layers: $N = 3$, $\varepsilon_{rf} = 2.33$, $\tan\delta_f = 0.0012$, $d_f = 1.6$ mm, $\varepsilon_{r1} = 2.2$, $\tan\delta_1 = 0.0009$, $d_1 = 3.175$ mm, $\varepsilon_{r2} = 1.07$, $\tan\delta_2 = 0.0009$, $d_2 = 3$ mm, $\varepsilon_{r3} = 2.2$, $\tan\delta_3 = 0.0009$, $d_3 = 0.127$ mm.



(a) (b) (c)

Fig. 5. Input impedance as a function of lower patch size. (a) $PL_1 = PW_1 = 8$ mm. (b) $PL_1 = PW_1 = 9$ mm. (c) $PL_1 = PW_1 = 10$ mm.

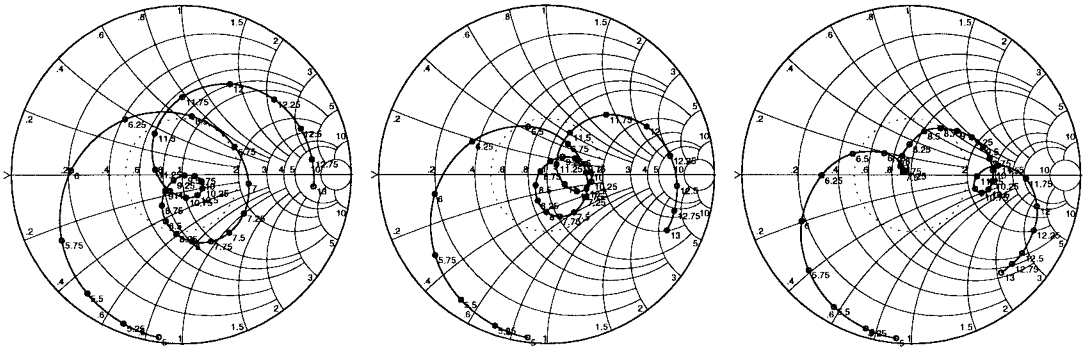


(a) (b) (c)

Fig. 6. Input impedance as a function of upper patch size. (a) $PL_2 = PW_2 = 9$ mm. (b) $PL_2 = PW_2 = 10$ mm. (c) $PL_2 = PW_2 = 12$ mm.

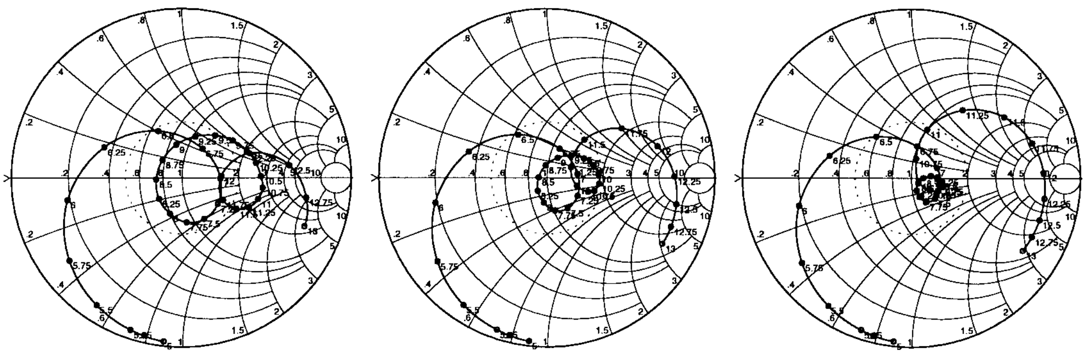
varying the upper patch dimension. Note the similarities between Figs. 5(a) and 6(c) and Figs. 5(c) and 6(a). These similarities show that it is not the absolute dimensions of each patch that govern the impedance behavior, but the relative size of each patch to the other that is important. When the two patches are overcoupled [the situation evident in Figs. 5(a) and 6(c)], this mutual resonance dominates the impedance behavior. Conversely, when the resonances of the patches are undercoupled [Figs. 5(c) and 6(a)], it is the mutual resonance between the lower patch and aperture which dominates. Achieving the proper balance between the two mutual resonances maximizes the bandwidth, and this situation is seen in Figs. 4(b), 5(b), and 6(b).

In Fig. 7, the lower substrate thickness is varied. The main effect of this parameter is on the coupling between the aperture and lower patch. With increasing thickness the coupling is reduced and, thus, the size of the corresponding loop in the impedance locus is smaller. The same effect occurs when using



(a) (b) (c)

Fig. 7. Input impedance as a function of Layer #1 dielectric thickness (a) $d_1 = 2.5$ mm. (b) $d_1 = 3$ mm. (c) $d_1 = 4$ mm.



(a) (b) (c)

Fig. 8. Input impedance as a function of Layer #2 dielectric thickness. (a) $d_2 = 2$mm. (b) $d_2 = 3$ mm. (c) $d_2 = 4$ mm.

a small aperture and is evident by the similarities in Figs. 4(a) and 7(c). In terms of design criteria, this signifies that when aperture size is increased, the lower substrate thickness must also be increased to maintain the same impedance behavior.

Fig. 8 shows the effect of upper substrate thickness on the impedance behavior. This affects the size of the upper frequency loop, as the coupling between the two patches is reduced with increased substrate thickness. This parameter also has an effect on the interaction between the two mutual resonances. At a thickness of 2 mm [Fig. 8(a)], the two mutual resonances are essentially decoupled, however, at 4 mm [Fig. 8(c)], a high degree of coupling exists between the mutual resonances, decreasing the size of the lower frequency loop.

V. Discussion

Some insight into the operation of a stacked patch antenna can be gained by examining the phase difference of the currents on the two patches. Interestingly, in all cases shown in this paper, it was found that near the top end of the frequency band the phase difference between the currents approaches 180°. As this happens, the antenna becomes a very poor radiator and this represents an upper limit to the bandwidth that can be obtained with the ASP or a stacked patch configuration in general. Therefore, to be an efficient radiator over the entire band, the mutual resonance between the aperture and lower patch must be lower in frequency than the stacked patch resonance. This also suggests that additional patches, while possibly providing a loading effect that can assist in impedance matching, will not enhance the bandwidth characteristics of the ASP as additional mutual resonances between the patches will exhibit the same behavior.

VI. Design Considerations and Results

Using the data provided in Section IV as a guide, an ASP antenna was designed, fabricated, and tested. Referring to the geometry shown in Fig. 1, the dimensions of the antenna were as follows.

Feed Parameters: $W_f = 0.5$ mm, $d_{\text{off}} = 5.4$ mm, $L_{stub} = 5.8$ mm, $\varepsilon_{rf} = 2.2$, $d_f = 0.635$ mm, $\tan\delta_f = 0.0009$.

Aperture: $SL = 16$ mm, $SW = 1$ mm.

Antenna Substrate: $N = 4$, $\varepsilon_{r1} = 1.07$, $d_1 = 1.2$ mm, $\tan\delta_1 = 0.0009$; $\varepsilon_{r2} = 2.2$, $d_2 = 3.175$ mm, $\tan\delta_2 = 0.0009$; $\varepsilon_{r3} = 1.07$, $d_3 = 3.1$ mm, $\tan\delta_3 = 0.0009$; $\varepsilon_{r4} = 2.53$, $d_4 = 0.508$ mm, $\tan\delta_4 = 0.003$.

Patch Elements: $PL_1 = 10.8$ mm, $W_1 = 20$ mm, $N_1 = 2$; $PL_2 = 11.2$ mm, $PW_2 = 20$ mm, $N_2 = 3$. Linearly polarized rectangular patches were used for additional bandwidth. For dual-linear or circular polarization, square patches, and a crossed slot could also be used in a similar configuration with only a 5–10% decrease in bandwidth.

The antenna substrate consisted of four layers of varying thickness. Each layer serves an individual purpose. Previous experience has shown that when using a dielectric slab for the bottom layer, even small air gaps between the slab and ground plane can significantly affect the input impedance. The bottom

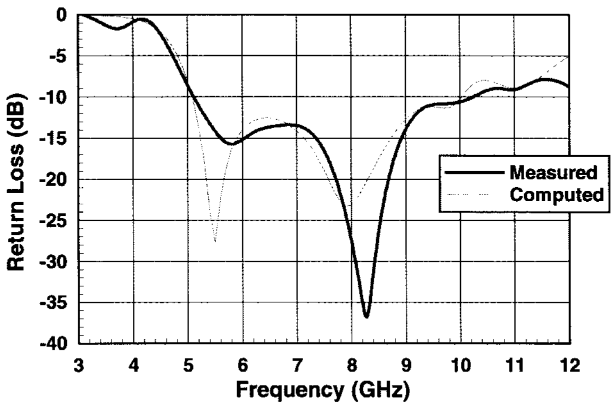


Fig. 9. Computed and measured return loss for ASP antenna.

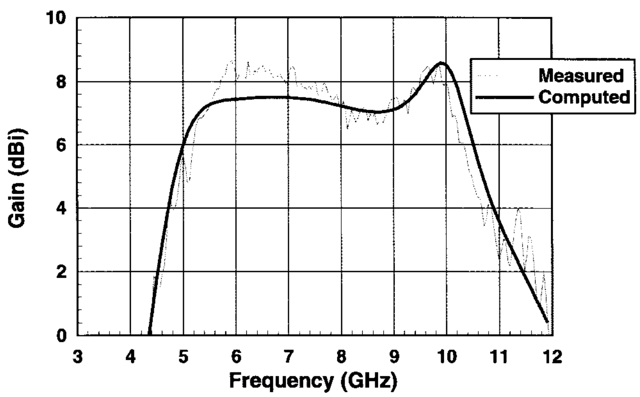


Fig. 10. Computed and measured gain for ASP antenna.

layer in this design, a 1.2-mm-thick foam substrate, serves as a buffer between the ground plane and the thick Duroid slab, minimizing the effect of any unintentional air gaps present in the experimental model. The combination of the next two layers, a thick Duroid layer followed by a thick foam layer, provides good bandwidth characteristics. Because foam is used for the third layer, a fourth dielectric layer was needed to facilitate etching of the upper patch.

Impedance matching was achieved by the use of dual offset feedlines, as discussed in Section III. The computed and measured return loss for the antenna is shown in Fig. 9. Good agreement is achieved with a computed bandwidth (SWR $<$ $2:1$) from 5.05 to 10.1 GHz (67%) and a measured bandwidth from 5.07 to 10.38 GHz (69%). Measured and computed gain for the antenna is shown in Fig. 10. Again, good agreement is achieved with a computed bandwidth (Gain $>$ 6 dB) from 5 to 10.5 GHz (71%) and a measured bandwidth covering the octave from 5.2 to 10.4 GHz (67%). The gain drops off quite rapidly near the band edges; at the lower band edge, this is primarily due to the sharp increase in return loss. However, at the upper band edge, the drop in gain is due to an increased level of back radiation, as the patches do not radiate efficiently.

Two other important factors in assessing the overall performance of the antenna are front-to-back ratio and surface wave efficiency. The ASP exhibits a lower front-to-back ratio than a typical aperture coupled patch antenna due to the use of a resonant aperture. The computed front-to-back ratio ranged from 8–14 dB over most of the band and dropped to 6 dB at the upper band edge. An improvement on these values can be achieved by placing a ground plane behind the aperture, or by using a third microstrip element behind the aperture as a reflector [13].

In some ASP configurations, a sizable amount of power can be lost to surface waves due to the thick substrates that are used. For this configuration, surface wave efficiency ranged from 82 to 90% over the band. By etching the patches on thin dielectric material and using thick foam substrates, the surface wave efficiency can be improved to over 95%. This type of configuration exhibits reduced bandwidth, but may be more attractive for phased-array applications.

VII. Conclusion

In this paper, design criteria for the ASP (aperture-stacked patch) microstrip antenna that utilizes a resonant aperture with stacked patches were presented. The characteristic action of the resonators in this antenna produces a greatly enhanced bandwidth over that exhibited by other aperture-coupled microstrip elements. Impedance-matching techniques were discussed and the effects of several key physical parameters of the antenna were examined. Results of this parameter study provide a good design guide for this antenna. It was also suggested that certain design variations, such as incorporation of additional patches, are not practical due to the behavior of the patch currents in a stacked patch configuration. A linearly polarized experimental design was presented from which an octave bandwidth was realized.

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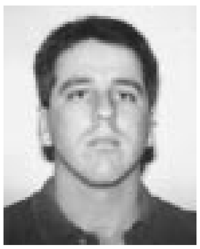

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