Design and Performance of Small Printed Antennas

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***Abstract*— In this paper, electrically small microstrip patches incorporating shorting posts are thoroughly investigated. These antennas are suitable for mobile communications handsets where limited antenna size is a premium. Techniques to enhance the bandwidth of these antennas are presented and performance trends are established. From these trends, valuable insight to the optimum design, namely broad bandwidth, small size, and ease of manufacturing, is given.**

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

I. Introduction

MICROSTRIP patches are currently being used for many applications due to several key advantages over conventional wire and metallic antennas. These advantages include low profile, light weight, and ease of fabrication and integration with RF devices. However, there are several applications where even the physically small size of a conventional microstrip patch antenna is still too large. One such scenario is for use on a mobile communications handset. Here, although the above mentioned features of a printed antenna are compatible with this technology, the operational frequency is too low. Frequencies of less than 2 GHz require conventional patches too large to be readily installed on typical dimensions of a mobile communications handset. Thus, several techniques have been proposed to effectively reduce the size of the printed radiator and so taking advantage of some of the other key points associated with printed technology. Using high dielectric constant material has been proposed [1], however, so far, only poor efficiency due to surface wave excitation and narrow bandwidths have been achieved. Also, the limited availability of low cost, low loss, high dielectric constant material is another problem with this method. In [2]–[6] shorting posts were used in different arrangements to reduce the overall size of the printed antenna. As shown in [4], the maximum reduction in physical size can be achieved if a single shorting post is used. Here, the radius of the circular patch was reduced by a factor of three, making the antenna size very suited for handset terminals. However, there are critical drawbacks with this form of printed antenna. In particular, the strong dependence of the input impedance on the close positioning of the shorting post with respect to the feed and once again the narrow impedance bandwidth. To date, the recorded bandwidths of the proposed shorted patches are significantly less than that required for typical digital cordless systems such as DECT (digital European cordless telephones) [7]. In this paper, the fundamental problems with shorted patches are addressed and techniques to alleviate them are proposed and investigated.

It should be noted that throughout this paper, the term shorted patch is used to describe a patch incorporating several shorting posts. It does not refer to the classical quarter-wave patch antenna where an edge of the radiator is terminated with a short circuit plane. The impedance behavior of the shorted patch radiator was qualitatively explained in [8] using simple circuit theory and so, for the sake of brevity, will not be included here. However, it is important to note that at a fixed frequency, the modified patch size can be increased or decreased, depending on the distance of the shorting pin from the feed. Of course, this over-simplified approach ignores coupling between the fields from the edges of the patch and the pins. As shown later in this paper, all of these relative dimensions of the printed antenna play a role in determining the impedance behavior of the radiator.

The organization of this paper is as follows: Section II presents the impedance and radiation characteristics of a shorted circular patch incorporating a single shorting post. The antenna is mounted on a relatively thick substrate with a low dielectric constant to enhance the bandwidth. A comparison between theory and experiment is provided; Section III presents a parameter study showing the effects of the height of the substrate, the dielectric constant of the material, the size of the feed and shorting pins; the effect of a cover layer on the electrical performance and manufacturing ease of the shorted patch is also provided. From this study, valuable insight into the optimum design of shorted patches is achieved; Section IV addresses the problem of the strong dependence of the impedance behavior of the shorted patch on the close proximity of the feed to the pin. Here, a simple technique is proposed which overcomes this short fall.

II. Characteristics of a Shorted Patch

Although conceptually quite easy to understand, a shorted patch is a complicated radiating structure. Thus, to obtain an accurate representation of the electrical performance of this antenna, a full-wave analysis is required. Throughout this work, an analysis based on a full-wave spectral domain Green's function/Galerkin's technique was utilized. Attachment modes similar to those introduced in [9] were used to model the discontinuities associated with the feed and shorting pins. In this section, validation of the analysis will be given as well as a method to increase the impedance bandwidth of a shorted patch to that required for commercial mobile applications.

Consider a circular probe-fed patch loaded with a single shorting post, as shown in Fig. 1(a). Using the philosophy

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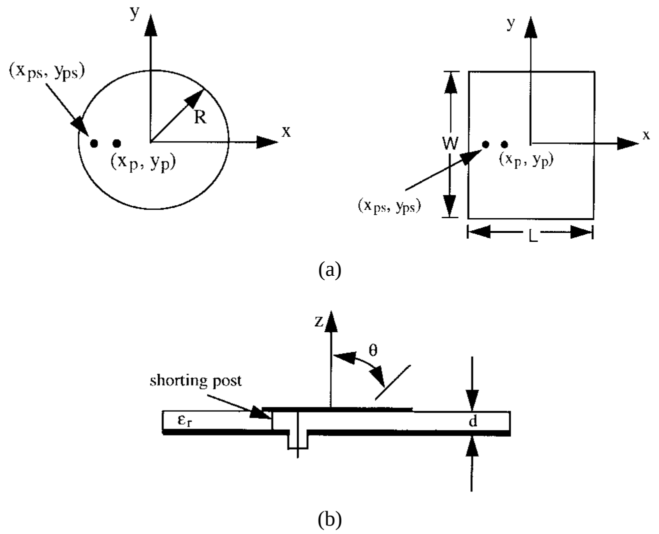

Fig. 1. Schematic of probe-fed patches incorporating single shorting posts. (a) Circular. (b) Rectangular.

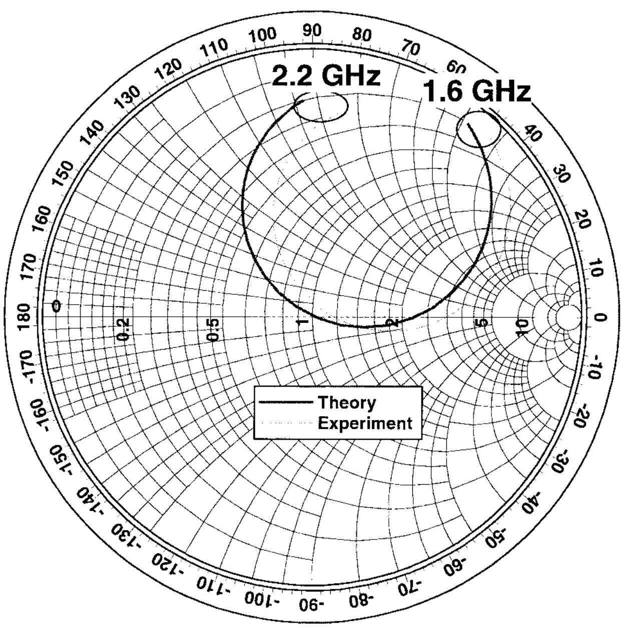

Fig. 2. Predicted and measured input impedance of circular probe-fed shorted patch (parameters: $\varepsilon_r = 1.07$, $\tan\delta = 0.015$, $d = 10$ mm, $R = 10.65$ mm, $x_p = 6.2$ mm, $y_p = 0$, $x_{ps} = 8.3$ mm, $y_{ps} = 0$, $r_0 = 0.325$ mm, $r_{0s} = 0.6$ mm).

adopted for conventional microstrip patch design, to achieve reasonable bandwidth a thick, low, dielectric substrate should be utilized. Fig. 2 shows the predicted and measured input impedance locus of a shorted patch designed for an input impedance of 50 Ω at a frequency of 1.9 GHz mounted on 10-mm foam (refer to Fig. 2 captions for the relevant dimensions). As can be seen from these plots, very good agreement between theory and experiment was achieved. The predicted and measured 10-dB return loss bandwidth was 6.3 and 6.8%, respectively. The impedance bandwidth is significantly more than that achieved using the technique outlined in [1] and also previously recorded bandwidths of shorted patches [2]–[6]. The radius of the patch is 10.65 mm,

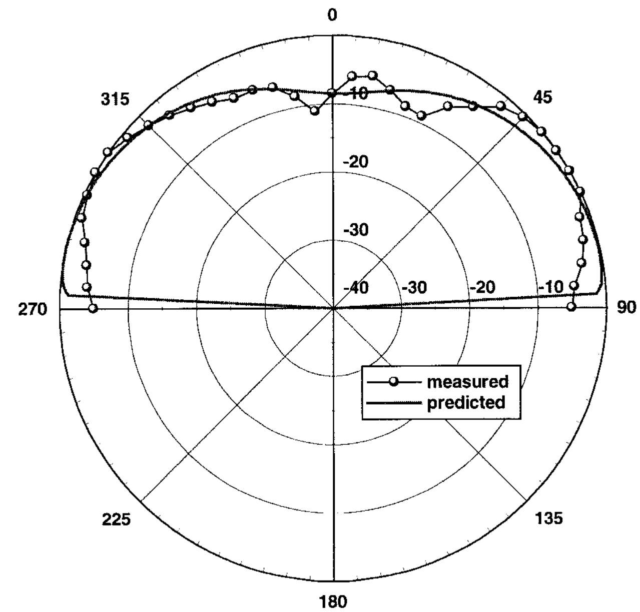

Fig. 3. Predicted and measured E-plane E_θ far-field radiation patterns of circular probe-fed shorted patch at 1.9 GHz.

allowing the antenna to be easily accommodated on a typical handset. It should be noted that to implement such an antenna for mobile communication terminals, a cavity-backed version (similar in principle to that presented in [10] for a conventional patch antenna) could be used to allow for easy integration into the handset itself. Slight discrepancies between the theoretical and experimental loci in Fig. 2 can be attributed to the thin layer of dielectric required to mount the conductor on the foam. This layer of dielectric (height of 0.254 mm, $\varepsilon_r = 2.2$) was not taken into account in the analysis. The separation distance between the feed pin and the shorting post (Δ) was 1.2 mm. A thorough investigation of this parameter will be presented in Sections III and IV.

The predicted and measured E_θ far-field radiation patterns in the E and H planes of the shorted circular patch are shown in Figs. 3 and 4, respectively. Once again, good agreement between experiment and theory was achieved. For the experiment, the shorted patch was mounted on a large ground plane (4 $\lambda_0\times$ 4 λ_0) to reduce diffraction off the edges. From the results presented in Figs. 3 and 4 the ripple commonly associated with a finite ground plane and more predominate in the E plane is still evident. The radiation patterns in Figs. 3 and 4 are similar to a top-loaded monopole. It is interesting to note that in the E plane, there is a slight dip in the pattern at broadside ($\theta = 0°$), not a deep null as usually expected for a top-loaded monopole. It can be postulated that this is due to the excitation of modes on the patch conductor. The extent of the decrease in magnitude is dependent on the relative position of the shorting pin and probe feed with respect to the center of the patch. It should be noted that although the H-plane cross-polarization level of this antenna (Fig. 4) is relatively high, for the application of mobile communications handsets this is not a major concern as much of these fields will diffract off the edges of the small finite ground plane within the handset [11]. A novel technique to reduce the magnitude of

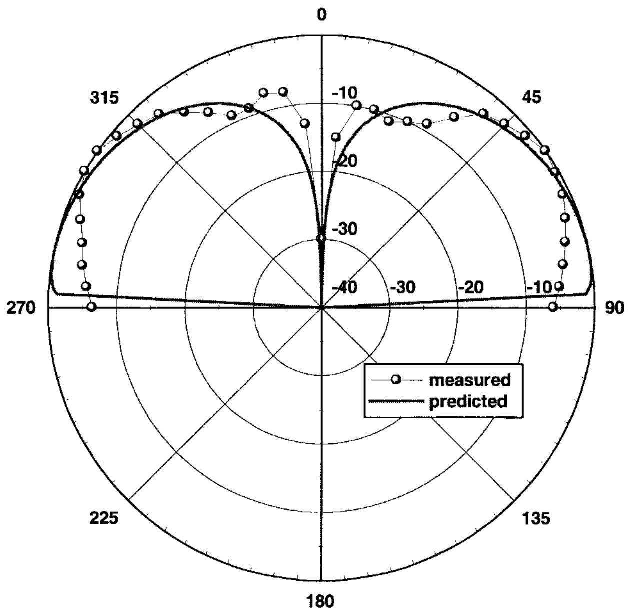

Fig. 4. Predicted and measured H-plane E_θ far-field radiation patterns of circular probe-fed shorted patch at 1.9 GHz.

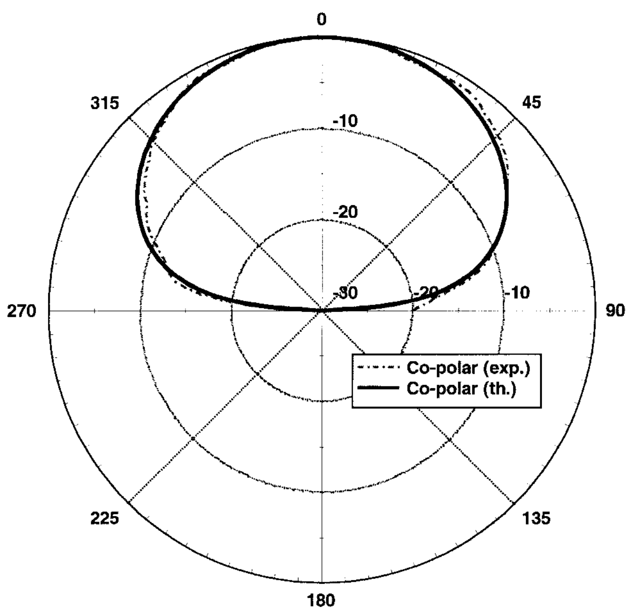

Fig. 5. Predicted and measured H-plane E_ϕ far-field radiation patterns of circular probe-fed shorted patch at 1.9 GHz.

the cross-polarization levels was presented in [12], however, at the expense of increased patch real estate. The H-plane copolarized field E_ϕ is very similar to that of a conventional patch and the predicted and measured pattern at 1.9 GHz is shown in Fig. 5. The predicted and measured gains of the antenna are 3.6 and 3.8 dBi, respectively. The location of the gain maximum is similar to a top-loaded monopole and also to the results presented in [3].

It should be noted that another solution for the given specification can be achieved using the rectangular shorted-patch configuration presented in Fig. 1(b). The dimensions of this case are: $L = 17.3$ mm, $W = 21.3$ mm, $x_p = 5.0$ mm, $r_0 = 0.325$ mm, $x_{ps} = 7.4$ mm, $r_{0s} = 0.6$ mm. Once

TABLE I
PARAMETER STUDY OF SHORTED CIRCULAR PATCHES (BW: BANDWIDTH, Δ: DISTANCE BETWEEN x_p AND x_{ps}, R: RADIUS OF PATCH)

Parameter	Action	Consequences
ε_r	$\downarrow$	$\uparrow\Delta$, $\uparrow$ **R**, $\uparrow$ **BW**
d	$\uparrow$	$\uparrow\Delta$, $\downarrow$ **R**, $\uparrow$ **BW**
x_{ps}/R	$\uparrow$ **(note: ≤ 1)**	$\downarrow\Delta$, $\downarrow$ **R**
r_{0s}	$\uparrow$ **(keeping r_0 constant)**	$\uparrow\Delta$, $\uparrow$ **R**
r_0	$\uparrow$ **(keeping r_{0s} constant)**	$\downarrow\Delta$, $\downarrow$ **R**
coverlayer	**Add**	$\uparrow\Delta$, $\downarrow$ **R**

again, the impedance bandwidth and radiation patterns are very similar to that presented for the circular patch case. For this reason and as the computational time required for the circular shorted patch is significantly less, only circular shorted patches will be considered herein. On a SPARC 10 workstation, the circular version takes 10 s per frequency point as compared to 166 s for the rectangular case.

III. PARAMETER STUDY OF SHORTED PATCHES INCORPORATING A SINGLE SHORTING POST

In this section, a parameter study of the shorted patch is given and yields valuable insight into the design of this radiator. A comparison of the properties of a shorted patch and a conventional patch was given in [13] and is not included here.

Schematics of circular and rectangular patches each incorporating a single shorting post are shown in Fig. 1. As can be seen from this figure, there are many degrees of freedom in the design of one of these radiators with each affecting the resonant frequency and input impedance of the antenna. Thus, there may be more than one solution for a given specification and given substrate parameters. Table I provides a summary of the effects of several parameters on the impedance and structural properties of a shorted patch radiator. For all the cases considered, the other parameters not being investigated were varied to ensure an antenna input impedance of 50 Ω at 1.9 GHz.

From the parameter study given in Table I, a design methodology can now be established. For reasonable bandwidths, thick foam substrates should be used. The use of an electrically thick substrate also reduces the radius of the patch conductor and increases Δ. The shorted patch is very suited to the inclusion of a coverlayer, which once again reduces the size of the patch as well as improves Δ. The radii of the pins also play an important role in the overall size of the patch conductor as well as Δ. Since a compromise must be made between R and Δ, we found good results can be achieved when r_{0s} is approximately 0.04 λ_0—approximately twice that of r_0. Once again, these values really depend on which is more important—the overall size of the antenna or the ease in fabrication.

The design procedure of a patch incorporating a single shorting post is relatively straightforward. As a starting point, the radius of the patch should be set to approximately $\lambda_g/16$ (where λ_g is the guided wavelength). The shorting post should be located at approximately 80–90% of this value. As pointed out in Table I, the closer the shorting pin to the edge, the

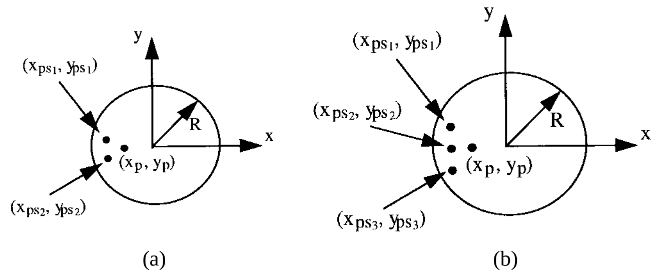

Fig. 6. Top view of probe-fed patches incorporating multiple shorting posts. (a) Two posts. (b) Three posts.

smaller the overall size of the patch. The probe feed should be located in close proximity to the shorting pin and then adjusted to achieve 50 Ω. Of course the design strategy will depend on the thickness of the substrate. As with the case for a conventional probe-fed patch etched on a thick substrate, the design is somewhat more complicated by the strong inductive nature of the electrically longer probe. However, this design procedure is still relatively accurate, requiring only slight adjustment of the dimensions.

IV. Technique to Improve Mechanical Tolerances

As was seen in the previous section, the close proximity of the feed and shorting pins is a major design flaw in the shorted patch antenna. Although some of the procedures outlined in Section III can reduce the stringent design tolerances on Δ, more robust solutions have yet to be provided. In this section, the issue of improving the manufacturing ease of a shorted patch is addressed and a simple technique is proposed.

The technique involves increasing the number of shorting posts. The philosophy behind this method can be extrapolated from some of the results presented in Section III. From Table I, the larger the radius of the shorting pin, the greater Δ. Another way of interpreting this is the stronger the shorting plane developed, the greater the Δ. Fig. 6 shows examples of this technique, where probe-fed circular patches consisting of two and three shorting posts are presented. As can be seen from these schematics there are even more degrees of freedom, in particular, the distance between the shorting pins or the angular displacement of the pins from the x axis ϕ (refer to Fig. 6).

Consider the patch with two shorting pins shown in Fig. 6(a). Using the same substrate parameters and pin radii given earlier, a patch configuration with the following dimensions was designed for 50 Ω input impedance at 1.9 GHz: $R = 13.2$ mm; $x_p = 4.95$ mm; $x_{ps1} = x_{ps2} = 11.08$ mm; and $\phi_1 = -\phi_2 = 10°$ (where ϕ_i is the angle between the ith shorting pin and the x axis). The 10-dB return loss bandwidth is approximately 7.9%. Thus, the improvement in bandwidth and Δ, here approximately 6 mm, are achieved at the cost of increased patch real estate. The predicted radiated E_θ in the E and H plane are similar to the patterns presented in Figs. 3 and 4, with the exception that there is less of a dip at broadside in the E plane by a factor of 2 dB. Thus, more power is being radiated with this configuration than a patch incorporating a single shorting post. There is also a more pronounced asymmetry in the E-plane pattern as a result of the presence of more shorting pins.

As mentioned before, another degree of freedom with the multiple shorting post antenna is the angular displacement of the posts. Consider the patch with two shorting posts with the angular displacement of the pins increased to $\pm 20°$. For an input impedance of 50 Ω at 1.9 GHz, the dimensions of this shorted patch are $R = 14.65$ mm, $x_p = 3.65$ mm, and $x_{ps1} = x_{ps2} = 12.7$ mm. The corresponding bandwidth of the shorted patch configuration is 9.4%. Thus, to achieve greater bandwidth the shorting posts should be positioned further apart, once again at the expense of increased patch area. An explanation of this phenomenon is that as ϕ increases, the coupling between the shorting pins decreases, as a function of $\cos\phi$. To counter this effect, stronger patch modes are required to maintain the coupling. Thus, the patch conductor size must be made larger.

Incorporating more shorting pins further increases the effective size of the shorting plane. A triple-post circular patch was designed for the previously given specifications and substrate parameters. The relevant dimensions are: $R = 15.4$ mm; $x_p = 2.35$ mm; $x_{p1} = 13.3$ mm; $x_{p2} = x_{p3} = 14.1$ mm; $\phi_1 = 0°$; and $\phi_2 = -\phi_3 = 20°$. The 10-dB return loss bandwidth of this patch configuration is approximately 10%, which is similar to the bandwidth of a conventional circular patch mounted on this substrate. As the number of shorting pins along the same plane increases, the performance of the printed antenna approaches that of a conventional quarter-wave patch. Once again the increase in bandwidth as well as Δ is at the cost of increased patch size. The radiation patterns for this configuration are similar to that presented before with the exception that the dip is further reduced by 1 dB. It is interesting to note that the magnitude of the H-plane cross-polarized fields are still relatively high. This finding is consistent with the postulation made in [14] about quarter-wavelength patches.

Recently, another means of improving the manufacturing ease was introduced in [15]. This technique resulted in similar trends to those presented here.

V. Conclusion

In this paper, electrically small printed antennas were thoroughly investigated using a rigorous analysis. Several shorted patches with bandwidths suitable for commercial digital cordless systems were designed and developed. The influence of all the variables of a shorted patch on the electrical and mechanical performance of this radiator were investigated and from the study a design methodology and procedure was established. A novel technique which alleviates the structural problems of a shorted patch were also proposed. In this paper, it has been shown that shorted patches are very suited to applications were antenna real estate is very limited, for example, for a mobile communications handset.

References

[1] T. K. Lo, C.-O. Ho, Y. Hwang, E. K. W. Lam, and B. Lee, "Miniature aperture-coupled microstrip antenna of very high permittivity," *Electron. Lett.*, vol. 33, pp. 9–10, Jan. 1997.

[2] D. H. Schaubert, F. G. Farrar, A. Sindoris, and S. T. Hayes, "Microstrip antenna with frequency agility and polarization diversity," *IEEE Trans. Antennas Propagat.*, vol. AP-29, pp. 118–123, Jan. 1981.
[3] C. Delaveaud, P. Leveque, and B. Jecko, "New kind of microstrip antenna: The monopolar wire-patch antenna," *Electron. Lett.*, vol. 30, pp. 1–2, Jan. 1994.
[4] R. B. Waterhouse, "Small microstrip patch antenna," *Electron. Lett.*, vol. 31, pp. 604–605, Apr. 1995.
[5] M. Sanad, "Effect of the shorting posts on short circuit microstrip antennas," in *Proc. IEEE Antennas Propagat. Symp.*, Seattle, WA, June 1994, pp. 794–797.
[6] I. Park and R. Mittra, "Aperture-coupled small microstrip antenna," *Electron. Lett.*, vol. 32, pp. 1741–1742, Sept. 1996.
[7] F. Ali and J. B. Horton, "Introduction to special issue on emerging commercial and consumer circuits, systems, and their applications," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1633–1638, July 1995.
[8] R. B. Waterhouse, S. D. Targonski, and D. M. Kokotoff, "Improving the mechanical tolerances and radiation performance of shorted patches," in *Proc. IEEE Antennas Propagat. Symp.*, Montreal, Canada, July 1997, pp. 1852–1855.
[9] J. T. Aberle, D. M. Pozar, and C. R. Birtcher, "Evaluation of input impedance and radar cross section of probe fed microstrip patch elements using an accurate feed model," *IEEE Trans. Antennas Propagat.*, vol. 39, pp. 1691–1697, Dec. 1991.
[10] F. Zavosh and J. T. Aberle, "Infinite phased arrays of cavity backed patches," *IEEE Trans. Antennas Propagat.*, vol. 42, pp. 390–398, Mar. 1994.
[11] J. Huang, private communication.
[12] R. B. Waterhouse, "Small printed antenna with low cross-polarized fields," *Electron. Lett.*, vol. 33, pp. 1280–1281, July 1997.
[13] R. B. Waterhouse and S. D. Targonski, "Performance of microstrip patches incorporating a single shorting post," in *Proc. IEEE Antennas Propagat. Symp.*, Baltimore, MD, July 1996, pp. 29–32.
[14] D. H. Schaubert, "A review of some microstrip antenna characteristics," *Microstrip Antenna Design*. New York: IEEE Press, 1995, pp. 59–67.
[15] R. B. Waterhouse and D. M. Kokotoff, "Novel technique to improve manufacturing ease of shorted patches," *Microwave Opt. Tech. Lett.*, pp. 37–40, Jan. 1998.

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