Effect of Curvature on the Performance of a Cylindrically-Conformal Cavity-Backed E-patch Antenna

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Abstract **─** The behavior of a cavity-backed E-patch antenna placed conformal to a cylindrical conducting surface is explored through simulations and experiment to determine the effects of curvature on antenna performance. It is shown that introducing a cavity backing reduces the bandwidth of an E-patch, but that the curvature of a conformal antenna partly compensates for the loss of performance. It is further shown that the curvature of a conformal antenna strongly affects both the co- and cross-polarization gain patterns.

Index Terms **─** Aircraft antennas, antenna measurements, antenna radiation patterns, conformal antennas, multifrequency antennas.

I. INTRODUCTION

E-patch antennas were introduced in [1] as a novel way to increase the bandwidth of conventional rectangular patch antennas. A typical E-patch is positioned on top of a low-permittivity spacer above a ground plane and fed through a coaxial probe. Use of a low permittivity dielectric (possibly air) produces maximal bandwidth. Since cavity-backed antennas are used in a wide variety of applications [2-4], a variant of this antenna explored here is to position the E-patch at the aperture of a rectangular dielectric-filled cavity as shown in Figure 1. Two parallel slots are cut into the patch in vertical symmetry with respect to the feed point so as to excite Mode 2 of the antenna (as described in [1]). The slot length L_s, slot width W_s, slot placement P_s, and cavity height h are all crucial to controlling the bandwidth of the antenna. The slots of the E-patch antenna allow it to resonate at two frequencies, and the bandwidth is determined primarily by the separation of the frequencies.

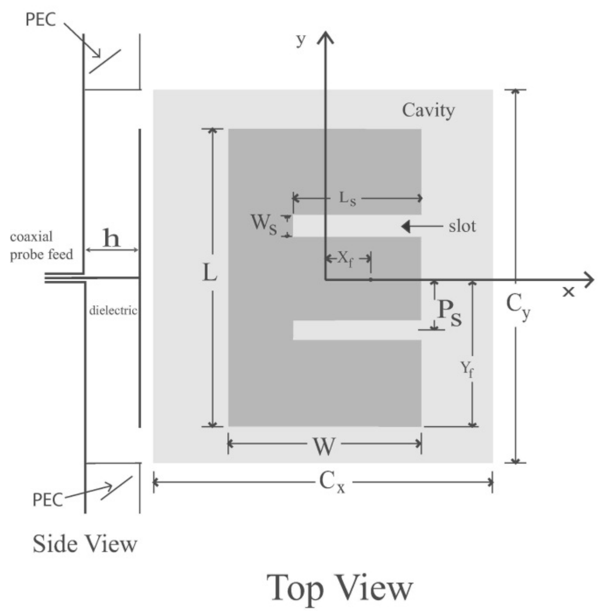

Fig. 1. Geometry of a planar cavity-backed E-patch antenna.

Patch antennas are appealing for aerospace applications because they may be easily conformed to a curved surface, such as an airplane wing or fuselage [5-9]. It is also possible to install a cavity-backed E-patch conformally, but the

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effect of surface curvature on the performance of an E-patch has not yet been investigated. It is important, in particular, to determine whether conformal installation has a deleterious effect on the enhanced bandwidth of the E-patch. In [10], the effect of conforming a rectangular patch antenna to the surface of a cylinder was investigated and the authors found that the bandwidth of the antenna increased and the pattern broadened. They did not, however, include a backing cavity, so it remains to understand how a backing cavity influences the fields and impedance of a conformal E-patch. To explore these effects, a cavity-backed E-patch is placed conformal to the surface of a perfectly conducting cylinder, and the properties of the antenna are examined through simulation as the radius of the cylinder is altered. The characteristics of a typical conformal cavity-backed E-patch are also examined experimentally, by installing a prototype antenna in an aluminum-coated tube.

II. TRADITIONAL AND CAVITY-BACKED E-PATCH ANTENNAS FOR L-BAND OPERATION

To serve as a baseline for comparison with the conformal cavity-backed E-patch, a traditional air-dielectric E-patch antenna was designed to operate with a return loss of at least 10 dB within the L-band frequency range 1200-1600 MHz. This covers the entire range between the L2 (1227.6 MHz) and L1 (1575.42 MHz) GPS operating frequencies. The design equations given in [11] were used as a starting point, and then trial and error was used to obtain the antenna with the dimensions shown in Table 1. The reflection coefficient (negative of the return loss in dB), as computed using the commercial solver Sonnet, is shown in Figure 2. It can be seen that the 10-dB bandwidth of the antenna extends from 1150-1650 MHz and thus meets the desired bandwidth criterion. Note that in the simulations, a ground plane of infinite extent was employed.

An air-filled backing cavity was then added to the E-patch and the dimensions of the antenna and cavity were adjusted in an attempt to produce the same 10-dB bandwidth (1200-1600 MHz) as with the traditional E-patch. Here computations were carried out using an in-house solver based on the finite-element boundary-integral method, again with a ground plane of infinite extent. Unfortunately, a trial-and-error approach was unable to achieve a return loss of 10 dB or greater over this band. So, Taguchi's optimization method [12,13] was implemented to adjust the dimensional parameters to try to meet the bandwidth criterion. The optimal design, with the dimensions shown in Table 2, has the reflection coefficient marked “Rectangular” in Fig. 3. It is seen that even after optimization, the cavity-backed antenna is not able to meet a 10-dB minimum return loss over the entire band 1200-1600 MHz. Operation near the L1 and L2 GPS frequencies is acceptable, but the return loss drops to about 6 dB at frequencies intermediate to these. It is thus concluded that a backing cavity has a somewhat deleterious effect on the wideband performance of an E-patch antenna.

Table 1: Dimensions of a traditional E-patch antenna designed for operation within the band 1200-1600 MHz

Dimension	Value in mm
L	107.1
W	91.2
X_f	5.5
Y_f	53.6
L_s	84.8
W_s	5.6
P_s	11.0
h	11.7

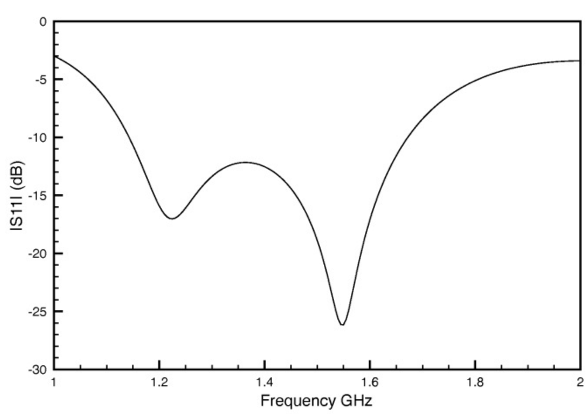

Fig. 2. Reflection coefficient for a traditional E-patch antenna. System impedance is 50Ω.

Table 2: Dimensions of a rectangular cavity-backed E-patch antenna designed for operation within the band 1200-1600 MHz

Dimension	Value in mm
L	96
W	83
X_f	37.5
Y_f	48
L_s	65
W_s	7
P_s	13
h	15.6
C_x	200
C_y	200

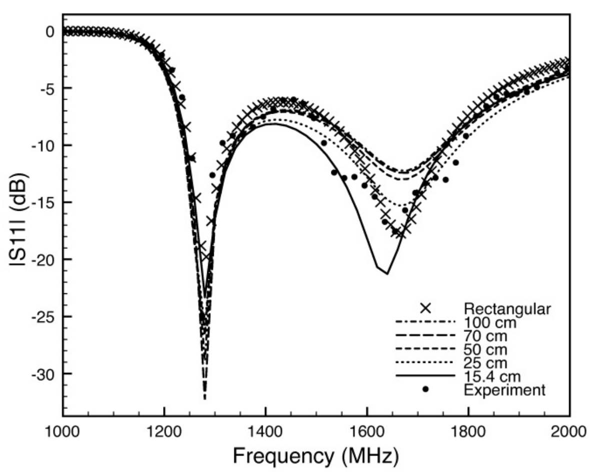

Fig. 3. Reflection coefficient for a cavity-backed E-patch antenna. Cavity is either planar, or conformed to the surface of a cylinder with various radii ρ. System impedance is 50Ω. Radius for the experimental antenna is 15.4 cm.

III. GEOMETRY OF A CYLINDRICALLY-CONFORMAL CAVITY-BACKED E-PATCH ANTENNA

Figure 4 depicts the geometry of a cavity-backed E-patch antenna placed conformal to the surface of a cylinder. In order to analyze how the curvature of the cylinder affects antenna performance, it is useful to start with the planar cavity-backed E-patch as a baseline. The manner in which the dimensions of the planar antenna given in Table 2 are maintained for the conformal E-patch can be seen by comparing Fig. 1 to Fig. 4. Dimensions of the planar antenna measured along y are maintained for the conformal antenna as dimensions measured along z. Dimensions measured along x become the curved distances measured as arc lengths given by $s = \rho\phi$, where ρ is the cylinder radius and ϕ is the angle subtended. Dimensions of the planar antenna measured along z, such as the cavity height h, are specified for the conformal antenna as a radial distance.

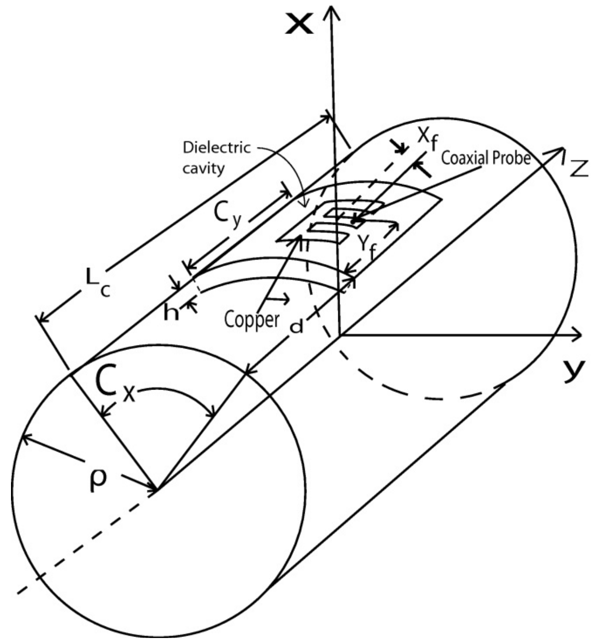

Fig. 4. Geometry of the cavity-backed E-patch antenna conformal to the surface of a cylinder of radius ρ.

IV. EFFECTS OF CURVATURE ON RETURN LOSS

The commercial EM solver HFSS was used to analyze both the planar cavity-backed E-patch antenna shown in Fig. 1 and the cylindrically-conformal cavity-backed E-patch shown in Fig. 4. The reflection coefficients found for various cylinder radii are shown in Fig. 3, referenced to 50Ω, with a cylinder length of $L_c = 100$ cm (except for the 15.4 cm radius case, which has $L_c = 122$ cm to match the experimental antenna). The largest radius of curvature (100 cm) produces a return loss near the second resonance significantly lower than the planar case (12 dB versus 18 dB at 1650 MHz). At the first resonance, the return loss is similar to that of the planar case, and at frequencies in between the resonances the return losses are also nearly the same at about 6 dB. Thus, like the planar cavity-backed antenna, the curved cavity-backed antenna cannot meet the bandwidth criterion. As radius is decreased, however, the return loss at the second resonance increases, as does the return loss between resonances. At a radius of 15.4 cm the return losses at the two resonances are nearly the same (although the frequency of the second resonance has decreased), and the return loss between the resonances has increased to about 8 dB. The effect of a highly curved surface is thus to improve the performance of the antenna between the L2 and L1 frequencies, although the 10 dB bandwidth criterion is still not met. Improved return loss bandwidth is probably due to a reduction in antenna Q produced by the enhanced radiation dampening introduced by the cylinder curvature.

V. EFFECTS OF CURVATURE ON GAIN PATTERNS

Figures 5 and 6 show the co-polarized gain patterns for a cavity-backed E-patch antenna conformal to a cylinder of various radii, simulated at 1300 MHz using HFSS. For cuts taken in the X-Z plane, negative values of θ indicate observations in the $x < 0$ plane, while positive values correspond to the $x > 0$ plane.

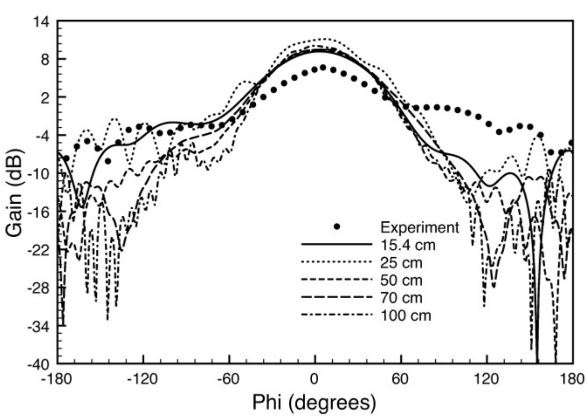

Fig. 5. Co-polarized gain pattern in the X-Y plane of a cylindrically conformal cavity-backed E-patch antenna at $f = 1300$ MHz. Radius of experimental antenna is 15.4 cm.

For cuts in the X-Y plane, curvature has very little effect (1 or 2 dB) on the broadside ($\phi = 0^\circ$) gain. However, as the radius of curvature is decreased, the gain away from broadside is significantly increased at most angles. At a radius of 15.4 cm, the front-to-back ratio (gain at $\phi = 0^\circ$ minus the gain at $\phi = 180^\circ$) is only 14 dB. Similar effects are seen for cuts in the X-Z plane, where the gain away from broadside increases and flattens considerably as the radius of curvature is reduced.

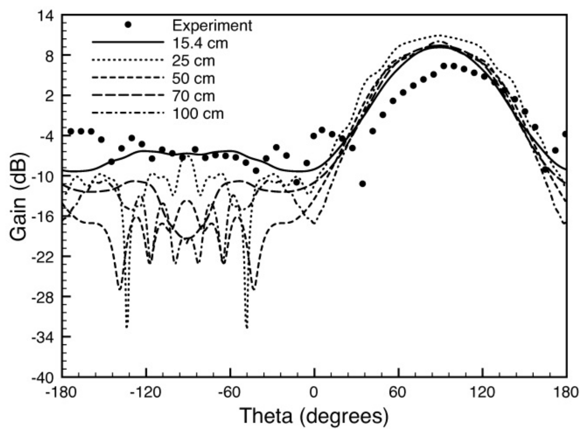

Fig. 6. Co-polarized gain pattern in the X-Z plane of the simulated cylindrically conformal cavity-backed E-patch antenna at $f = 1300$ MHz. Radius of experimental antenna is 15.4 cm.

Similar effects on pattern were described in [2] for a rectangular patch antenna placed conformal to a circular cylinder. With a patch radiating edge length of about 60% of the cylinder radius, similar to the E-patch case of $\rho = 15.4$ cm, a front-to-back ratio of 15 dB was found. Pattern filling away from broadside is probably due to the fact that as the cylinder radius becomes comparable to the patch edge size, the radiating edges of the patch become significantly closer together, reducing the directivity and increasing the side lobes.

Effects of curvature on the cross-polarized gain patterns are more pronounced, but in all cases the cross-polarized gain is significantly below the co-polarized gain. The largest cross-polarized gain was seen in the X-Z plane at broadside, with a value of about -5 dB. In the X-Y plane the cross-polarized gain never rises above -20 dB, regardless of the radius of curvature.

Although not shown here, similar effects of curvature on gain pattern can be observed at the second resonance frequency.

VI. COMPARISON TO EXPERIMENT

To verify the results predicted by simulation, a prototype conformal cavity-backed antenna was constructed using an 122 cm long, 15.4 cm radius tube covered by aluminum foil (see Fig. 7). An aperture was cut into the tube, and a cavity was constructed as shown in Fig. 4 using high-density Styrofoam and copper tape. A copper E-patch was placed in the aperture on top of the Styrofoam and the center conductor of a coaxial feed was passed through the cavity from inside the cylinder and soldered to the patch. All dimensions of the prototype correspond to the values used in the simulations as shown in Table 2.

Fig. 7. Photo of prototype. Radius of cylinder is 15.4 cm.

The reflection coefficient for the prototype antenna measured with a 50Ω system is shown in Fig. 3 and compared with the results for the simulated antenna. The measured return loss is very close to that of the antenna simulated on a 15.4 cm radius cylinder, except near the second resonance where there is some discrepancy, probably due to standing waves in the aperture caused by the copper tape used to attach the cavity to the aluminum tube. In any event, the measured return loss verifies that placing the antenna conformal to the curved surface does not have a deleterious effect on the bandwidth.

The measured co-polarized X-Y and X-Z plane gain patterns of the prototype are shown in Figs. 5 and 6, respectively. Although the measured patterns show slightly less gain at broadside than the simulations (about 3 dB less), they verify that the gain of the strongly-curved antenna is fairly high and quite flat away from broadside, and that the front-to-back ratio is not large (about 12 dB, or slightly less than predicted in the simulations). The cross-polarization patterns could not be measured accurately away from broadside due to the limited dynamic range of the measurement system, but showed trends similar to the simulations near broadside.

VII. CONCLUSION

The effects of curvature on a cylindrically-conformal cavity-backed E-patch antenna are examined experimentally and through simulations. It is shown that it is difficult to achieve the same wideband return loss with a cavity-backed antenna as with a classic planar E-patch. However, when the cavity-backed antenna is conformed to a cylinder, the curvature of the antenna may be used to improve the bandwidth and approach the performance of the traditional E-patch antenna. In contrast, high curvature degrades the patterns of the conformal antenna somewhat, producing gain patterns with a reduced co-polarized front-to-back ratio and significant cross-polarization gain at broadside.

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REFERENCES

[1] F. Yang, X.-X. Zhang, and Y. Rahmat-Samii, “Wide-band E-shaped patch antennas for wireless communications,” *IEEE Trans. Antennas Propagat.*, vol. 49, no. 7, pp. 1094-1100, July 2001.

[2] N. Rahman, A. Sharma, M. Asfar, S. Palreddy, R. Cheung, "Dielectric characterization and optimization of wide-band, cavity-backed spiral antennas," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 2, pp. 123 - 130, February 2011.

[3] D. Caratelli, A. Yarovoy, "Design and Full-Wave Analysis of Cavity-Backed Resistively Loaded Circular-End Bow-Tie Antennas for GPR Applications – Part I," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25, no. 10, pp. 809 - 817, October 2010.

[4] D. Caratelli, A. Yarovoy, "Design and Full-Wave Analysis of Cavity-Backed Resistively Loaded Circular-End Bow-Tie Antennas for GPR Applications - Part II," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25, no. 10, pp. 818 - 829, October 2010.

[5] K. M. Luk, K. F. Lee, and I. S. Dahele, "Analysis of the cylindrical rectangular patch antenna," *IEEE Trans. Antennas Propagat.*, vol. AP-37, no. 2, pp. 143-147, Feb. 1989.

[6] X. Liu, Y. Chen, Y. Jiao, and F. Zhang, "Conformal low-profile E-shaped patch antenna with unequal thickness substrate," *Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, 16-17 August, Hangzhou, China, pp. 624-627, 2007.

[7] R. T. Jacobs, A. Kost, H. Igarashi, and A. J. Sangster, "Analysis of planar and curved microstrip antennas," *J. Microwaves and Optoelectronics,* vol. 6, no. 1, pp. 96-110, 2007.

[8] M. Redondo Gonzalez, "Analysis of conformal antennas for avionics aplications," Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, January 2007.

[9] D. H. Werner, R. J. Allard, R. A. Martin, and R. Mittra, "A reciprocity approach for calculating radiation patterns of arbitrarily shaped microstrip antennas mounted on circularly cylindrical platforms," *IEEE Trans. Antennas Propagat*., vol. 51, no. 4, pp. 730-738, April 2003.

[10] J. S. Dahele, R. J. Mitchell, K. M. Luk, and K. F. Lee, "Effect of curvature on characteristics of rectangular patch antenna," *Electronics Letters*, vol. 23, no. 14, pp. 748-749, July 2, 1987.

[11] A. Bzeih, S. A. Chahine, K. Y. Kabalan, A. El-Hajj, A. Chehab, "Empirical formulation and design of a broadband enhanced E-patch antenna," *National Radio Science Conference*, Cairo, Egypt, pp. 1-9, March 13-15, 2007.

[12] W.-C. Weng, F. Yang, V. Demir, and A. Z. Elsherbeni, "Linear antenna array synthesis using Taguchi's method: a novel optimization technique in electromagnetics," *IEEE Trans. Antennas Prpagat*., vol. 55, no. 3, pp. 723-730, March 2007.

[13] Gardner, "A Conformal Taguchi Optimized E-patch Antenna," M.S. Thesis, Michigan State University, East Lansing, MI, Dec. 2010.

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