

# Characteristics of Double Exponentially Tapered Slot Antenna (DE TSA) Conformed in the Longitudinal Direction Around a Cylindrical Structure

George E. Ponchak, *Senior Member, IEEE*, Jennifer L. Jordan, and Christine T. Chevalier, *Student Member, IEEE*

**Abstract**—The characteristics of a double exponentially tapered slot antenna (DE TSA) as a function of the radius that the DE TSA is conformed to in the longitudinal direction is presented. It is shown through measurements and simulations that the radiation pattern of the conformed antenna rotates in the direction through which the antenna is curved, and that diffraction affects the radiation pattern if the radius of curvature is too small or the frequency too high. The gain of the antenna degrades by only 1 dB if the radius of curvature is large and more than 2 dB for smaller radii. The main effect due to curving the antenna is an increased cross-polarization in the E-plane.

**Index Terms**—Conformal antenna, Double Exponentially Tapered Slot Antenna (DE TSA), slot-line antenna.

## I. INTRODUCTION

THE family of Tapered Slot Antennas (TSA's) are useful because they have a wide 10 dB return loss bandwidth, are easy to fabricate on a variety of substrates using simple printed circuit board fabrication processes, and have good radiation pattern characteristics with moderate gain of approximately 8 dBi [1]. The first implementation of a TSA was a stripline fed antenna formed in the ground planes in 1974 [2], and the first printed slot antenna (1979) was an exponentially tapered slot, the Vivaldi Antenna [3]. Various forms of TSA's have been summarized [4]. However, even though TSA's have been in the literature for 30 years, there are many questions about them that have not been addressed, including the physics behind their radiation [1]. Typically, TSA's are endfire antennas that are useful for phased array antennas. However, it has also been noted that because they may be printed on thin, soft substrates such as Liquid Crystal Polymer (LCP), they may be conformal [1], [5], [6].

In [5], a brief summary of an experiment about wrapping a

TSA around a foam cylinder with the discontinuity in the transverse and longitudinal direction is presented. Only the effect on gain is described, with no discussion of the radiation pattern. A Double Exponentially Tapered Slot Antenna (DE TSA), a variation of the Vivaldi Antenna, designed for Ultra Wide Band (UWB) applications conformed over a gently rounded foam shape in the longitudinal direction is described in [6]. It was shown that the main beam is skewed towards the direction of curvature. However, there has not been an in depth exploration on the effect of conforming a TSA around a curved structure.

In this paper, experimental and simulated characteristics of a DE TSA designed for 3 to 10 GHz and conformed in the longitudinal direction around cylindrical, foam structures is presented. The gain, 3dB beamwidth, cross polarization level, and beam direction are presented for different cylinder radii.

## II. DE TSA DESCRIPTION

A DE TSA was fabricated with 18  $\mu\text{m}$  thick copper on a 200  $\mu\text{m}$  thick LCP substrate, which has a dielectric constant of  $\epsilon_r = 3.1$  and a loss tangent of 0.003 [7]. The physical properties of LCP provide flexibility to conform the antenna around tight radii. The geometry of the DE TSA was optimized for the antenna to operate over the frequency range of 4 to 10 GHz when held in a perfectly flat shape. Figure 1 shows an artist drawing of the DE TSA with all dimensions and the equations for the exponential tapers. The slotline width at the start of the taper, after the rectangular section of uniform slotline, is 240  $\mu\text{m}$ . Standard photolithography processes and copper etching are used to define the DE TSA.

The radii of curvature are given in Table 1. Note that, throughout the paper, the data is presented as a function of the angle that the DE TSA wraps around a cylinder, with the uniform section of slotline held flat. For example, for the cylinder with a radius of 6.685 cm, the DE TSA wraps one quarter, or 90°, around the cylinder. Figure 2 shows an artist rendition of the curved DE TSA wrapped 90° around a cylinder.

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G. E. Ponchak and J. L. Jordan are with NASA Glenn Research Center, Cleveland, OH 44135 USA (george.ponchak@ieee.org, tel: 216-433-3504; Jennifer.Jordan@grc.nasa.gov).

C. T. Chevalier is with Analex Corp at NASA Glenn Research Center, Cleveland, OH 44135 USA (Christine.Chevalier@grc.nasa.gov)

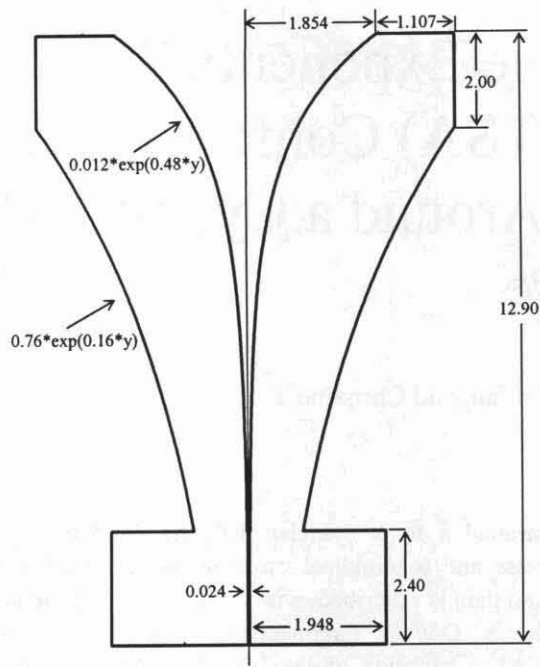


Figure 1: Schematic of DETSA with dimensions in cm.

Table 1: Dimensions of DETSA radii of curvature.

Radius (cm)	Radius ( $\lambda_0$ at 6 GHz)	Angle DETSA wraps around circle (degree)
flat	flat	
4.46	0.89	135
6.685	1.38	90
13.37	2.68	45
26.74	5.35	22.5

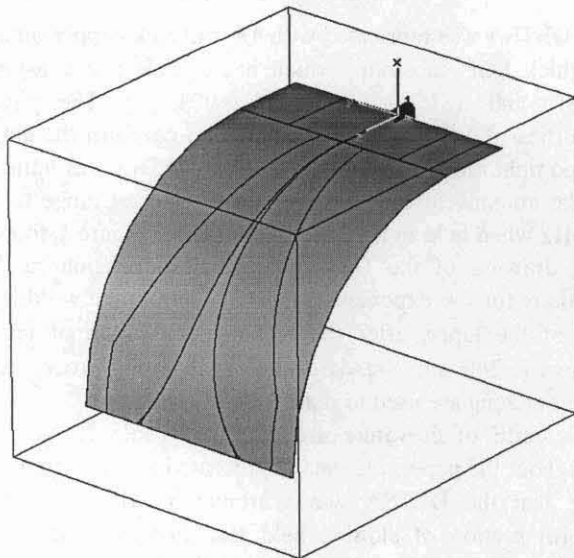


Figure 2: Schematic of DETSA wrapped 90° around cylindrical structure.

### III. RETURN LOSS AND RADIATION PATTERN MEASUREMENT TECHNIQUE

The form of the DETSA was held by placing the antenna between two pieces of Styrofoam, which also provided structural support. The Styrofoam shape is cut on a band saw, which introduces small variations (errors) to the shape. The beginning of the taper is placed where the Styrofoam starts to curve.

Two coax to slotline launchers were used in the paper. First, to measure the return loss of the antennas, an inline, coax to microstrip/coplanar waveguide launcher with three of the four ground connections sawed off was used. It was found that this yielded good impedance match, but symmetric currents were not established on the slotline. Therefore, for radiation pattern characteristics, the outer conductor of a semi-rigid coaxial waveguide is soldered onto one side of the slotline perpendicular to the slot at the edge of the board and the center conductor is extended to and soldered to the opposite side of the slotline [8]. Although the impedance match was not optimum, simulations and measurements showed that symmetric currents are established on the slotline, which is critical for radiation pattern characterization.

Using an HP 8510 Vector Network Analyzer,  $|S_{11}|$ , return loss measurements were taken to verify the bandwidth of each DETSA. A piece of RF absorber was used to minimize radiation from nearby metal surfaces during  $S_{11}$  return loss characterization. Although the symmetric excitation method described earlier produced good radiation patterns, the return loss measurements were poor. Therefore, the presented return loss measurements, seen in Fig. 3, use a coaxial feed.

Far-field radiation E and H plane measurements were taken in a calibrated far-field antenna range with a wide bandwidth 2 to 18 GHz rigid horn antenna transmitting to the DETSA. Measurements were taken from 3 to 9 GHz in 2 GHz increments. E-plane measurements were taken in alignment with the plane of the excitation feed ( $yz$  plane in Fig. 2), rather than in the direction of maximum H-plane radiation. As will be shown in Section V, taking E-plane measurements in the direction of maximum H-plane would have required cutting 16 blocks of Styrofoam at specific angles. Thus, simulated E-plane patterns in the direction of the H-plane maximum beam are used.

### IV. SIMULATION METHOD

The transient solver of the software package CST Microwave Studio [9] was used to simulate the DETSAs. The substrate material is of the type Normal with  $\epsilon_r = 3.1$ . The antenna is patterned with the material PEC (perfect electric conductor). All materials are lossless. The Styrofoam used in the experiment to hold the DETSA was not modeled. The complex antenna shape is drawn using the polygon curve tool which is then extruded to add metal thickness. Initially a coax with an extended center conductor and a pin from the outer conductor (ground) was used in conjunction with a waveguide port to excite the antenna. However this yielded asymmetric currents and farfields. Therefore, a discrete S-parameter port

with an impedance of  $50 \Omega$  was used to excite the antenna. Automatic meshing of eight meshlines per wavelength was used. For the flat DETSA this yields 555,540 mesh cells. With dual 2.8 GHz processors the simulation took 5.25 hours to complete. For the 45 degree curved DETSA this yields almost five million mesh cells, taking 15.5 hours to complete. The gain of each antenna and the farfields in several planes were monitored.

V. RESULTS

The measured return loss is shown in Fig. 3 as a function of the degree of curvature. It is seen that the 10 dB bandwidth is from 3 to 10 GHz, regardless of the degree of curvature.

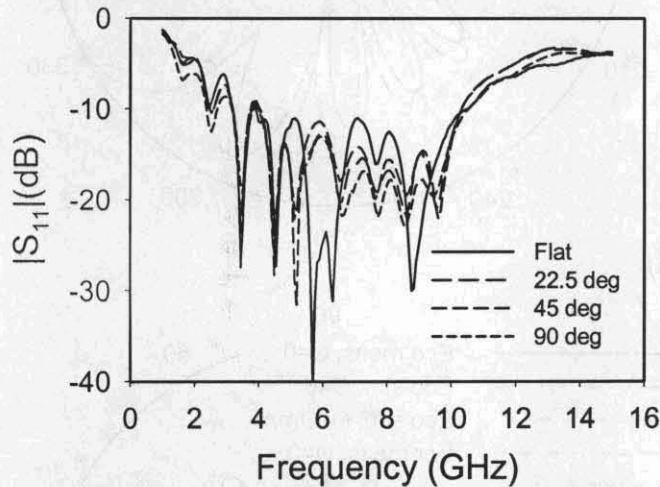
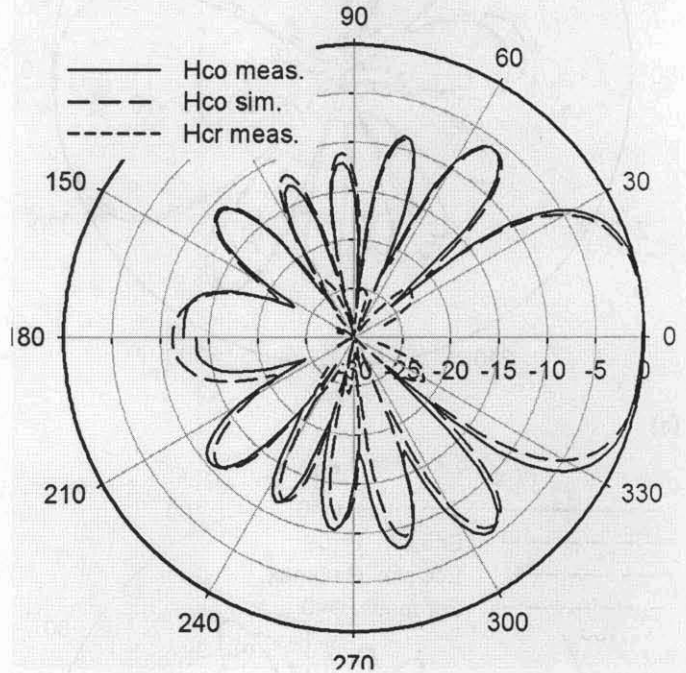


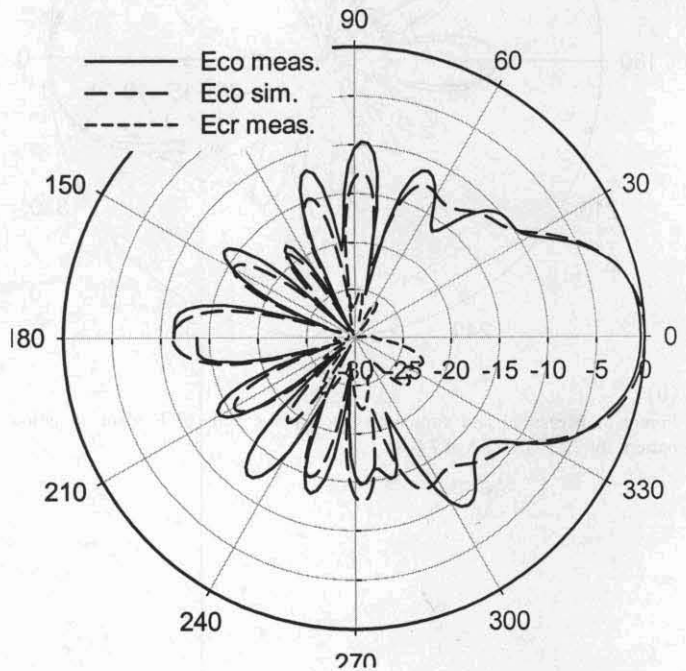
Figure 3: Measured return loss of DETSA as a function of frequency and degree of curvature.

The radiation pattern for the flat DETSA and DETSA's conformed in the longitudinal direction 22.5, 45, and 90° around cylindrical structures are shown in Figs. 4, 5, 6, and 7 respectively. The simulated cross-polarization values are too low to be plotted with the measured data and are not shown on the figures for clarity. First, it should be noted there is excellent agreement between the measured and simulated radiation patterns. This agreement permits the use of only simulated data for a few cases (E co-polarization at angle of maximum H co-polarization) where it is too difficult to configure the antennas for measurements. By comparing the flat DETSA H plane pattern with the 22.5 and 45° curved DETSA patterns, it is seen the number of nulls and lobes does not change as the antenna is conformed. Furthermore, the location of the nulls and lobes relative to the main beam remains approximately equal as the antenna is conformed. Therefore, the H plane pattern appears to be a simple rotation towards the direction of curvature. As the radius of the cylinder decreases, or the frequency increases, diffraction effects increase, and the pattern below the antenna is affected. This is seen for the 90° curved antenna shown in Fig. 7a; note the larger sidelobes in the direction of 285°. The H plane radiation pattern of the 135° curved antenna, not shown, is severely affected by diffraction. The angle that the H plane pattern rotates, or the angle of the main beam, is presented in Fig. 8 for all of the antennas. It is seen that the main beam is

skewed towards the direction that the antenna is curved towards, but that it is not in the direction that is tangent to the end of the antenna. As an approximation, the main beam is pointed in the direction of the tangent of the DETSA at one third of its length from the feed line. A secondary observation is that the main beam points more towards the direction tangent to the DETSA at the end as the frequency increases. This agrees with the observation in [6].

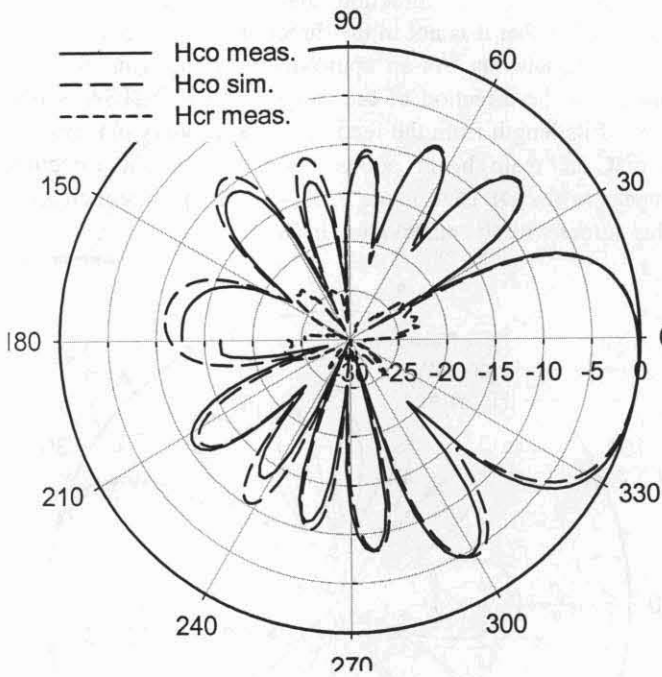


(a)

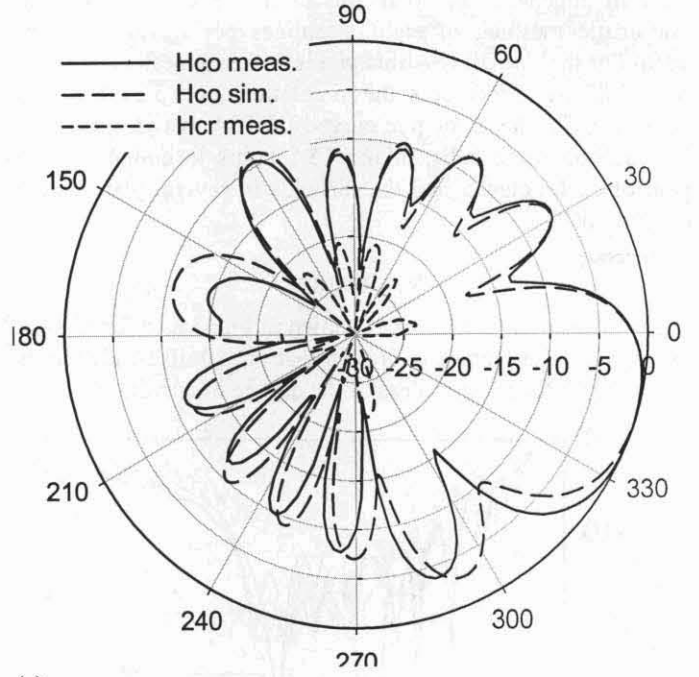


(b)

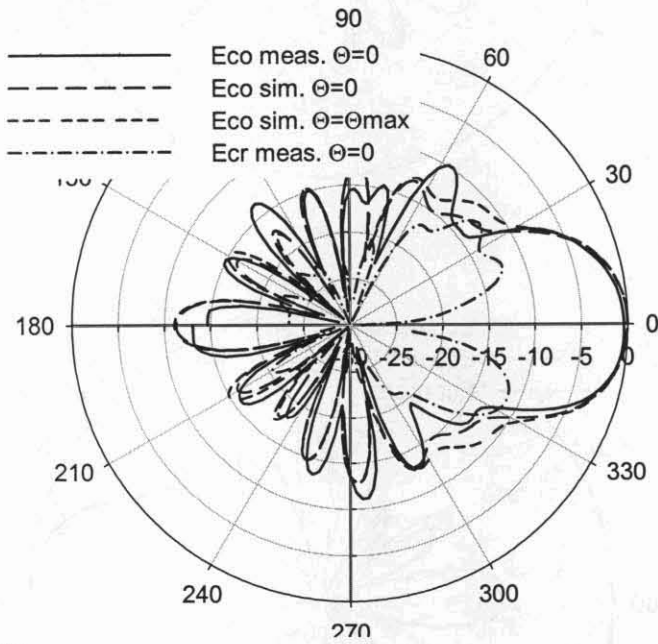
Figure 4: Measured and simulated (a) H plane and (b) E plane radiation pattern for flat DETSA at 7 GHz.



(a)

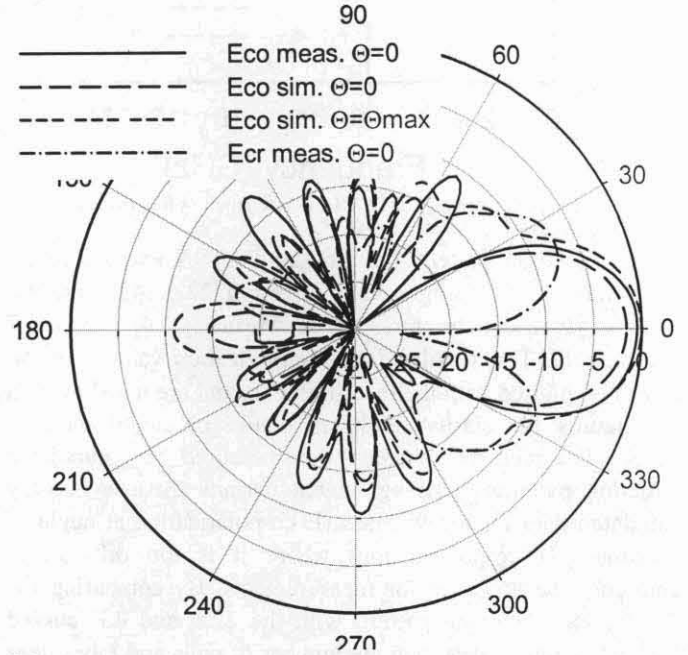


(a)



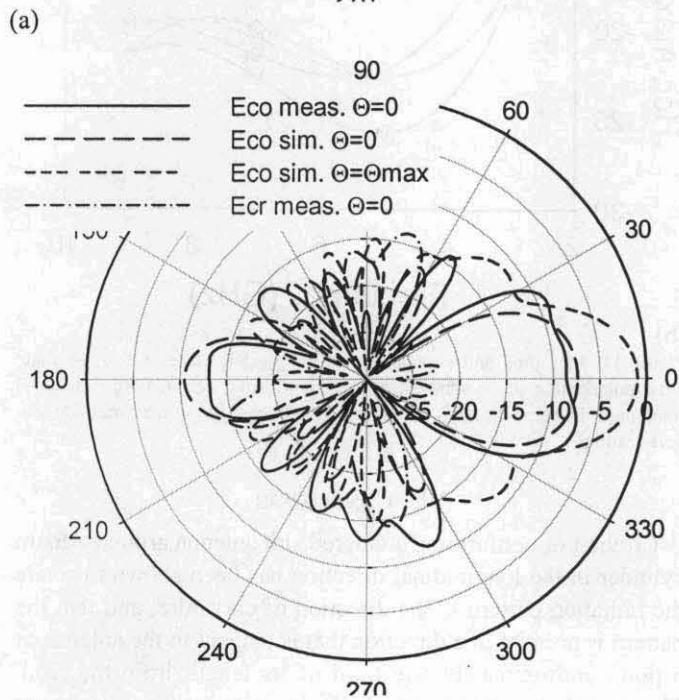
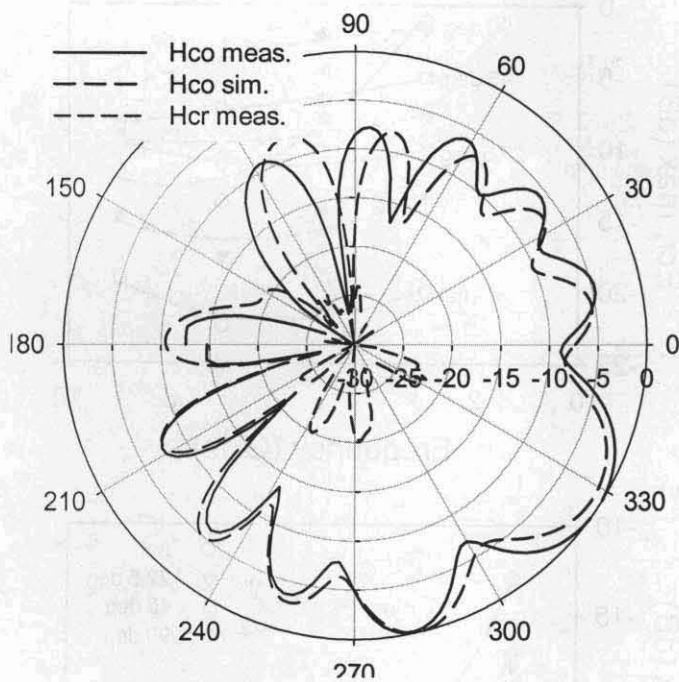
(b)

Figure 5: Measured and simulated (a) H plane and (b) E plane radiation pattern for 22.5° DETSA at 7 GHz.



(b)

Figure 6: Measured and simulated (a) H plane and (b) E plane radiation pattern for 45° DETSA at 7 GHz.



(a)  
(b)  
Figure 7: Measured and simulated (a) H plane and (b) E plane radiation pattern for 90° DETSA at 7 GHz.

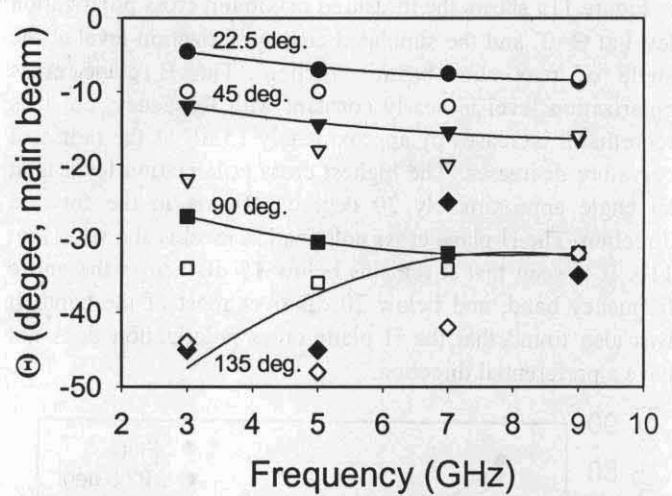


Figure 8: Measured and simulated angle of maximum radiation in H plane as a function of degree of curvature (solid symbols are simulated, open symbols are measured).

The antenna gain is shown in Fig. 9. The measured gain has been corrected for the coaxial to slotline transition return loss, but not for any attenuation, while the simulated gain assumes a lossless antenna with ideal mode excitation. It is seen that the gain increases with frequency for each antenna as expected for TSA's. Fig. 9 also shows that the gain decreases by only 1 dB for gently curved antennas compared to the flat DETSA, DETSA wrapped 45° or less around cylinder, but if the radius of curvature is greater, the gain decreases by an average of 2 dB across the frequency band. Interestingly, the gain for 22.5° and 45° curvature is almost the same.

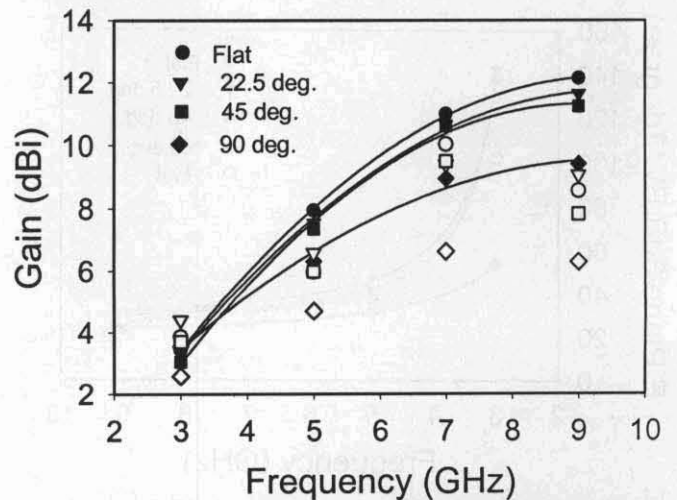
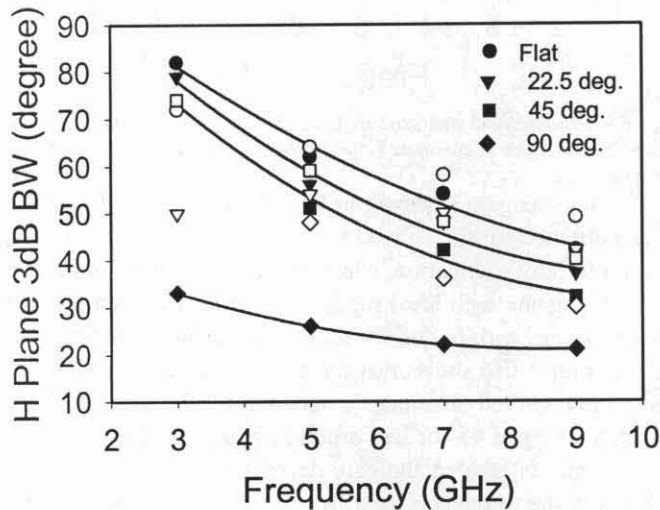


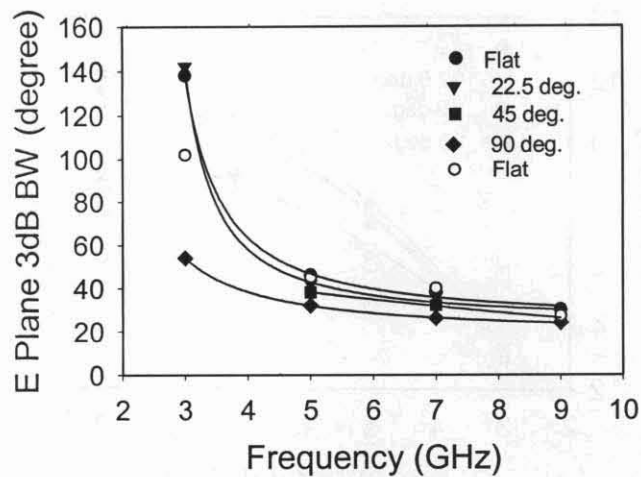
Figure 9: Measured and simulated gain of DETSA as a function of degree of curvature (solid symbols are simulated, open symbols are measured)

The beam shape obviously changes as the antennas are curved, and this is summarized in Fig. 10, where the 3 dB beamwidth is plotted. Again, the curved DETSA behaves similar to the flat DETSA, with 3dB beamwidth decreasing with frequency. The beamwidth decreases as the rate of antenna curvature increases, with the main beam in the H plane decreasing by approximately 25°. The E plane beamwidth is large at 3 GHz, but it is comparable to the H plane beamwidth at higher frequency.

Figure 11a shows the measured maximum cross polarization level at  $\Theta=0^\circ$  and the simulated cross polarization level at the angle of maximum beam direction. The E plane cross polarization level is nearly constant with frequency, but it is seen that it increases by approximately 15 dB as the radius of curvature decreases. The highest cross polarization level is at an angle approximately 30 degree off axis in the forward direction. The H plane cross polarization level is shown in Fig. 11b. It is seen that it remains below 15 dB across the entire frequency band, and below 20 dB over most of the band. It was also found that the H plane cross polarization does not have a preferential direction.

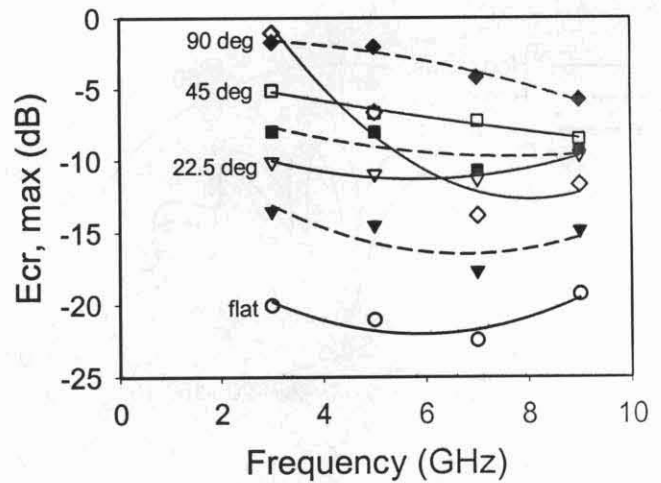


(a)

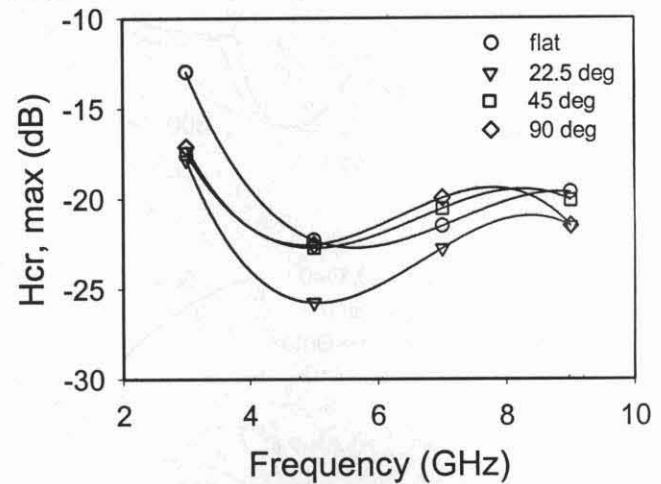


(b)

Figure 10: Measured and simulated (a) H plane and (b) E plane 3 dB beamwidth (solid symbol are simulated, open symbol are measured)



(a)



(b)

Figure 11: Measured and simulated maximum (a) E plane and (b) H plane cross polarization (open symbols are measured, solid symbols are simulated) (measured E plane at  $\theta=0$ , simulated E plane at  $\theta$  of maximum H co-polarization)

## VI. CONCLUSION

Curving or conforming a tapered slot antenna around a foam cylinder in the longitudinal direction has been shown to rotate the radiation pattern in the direction of curvature, and that the pattern is pointed in a direction that is tangent to the antenna at a point approximately one third of its length from the feed. The gain decreases by only 1 dB for large radii of curvature, but the E plane cross polarization level increases by 15 dB for the same large radius of curvature. It is noted that a DETSA without the rectangular pad at the feed point, used for soldering the coaxial launcher, was simulated, and the simulations showed that the conclusions in the paper are not effected by the pad. The pad only caused a small ripple on the pattern.

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