Design and Fabrication of an Axial Mode Helical Antenna

William Coburn, Canh Ly, Timothy Burcham, Russell Harris and Amid Bamba
U.S. Army Research Laboratory
Adelphi, MD 20783
wcoburn@arl.army.mil, ly@arl.army.mil, burcham@arl.army.mil, rharris@arl.army.mil, amid.bamba@arl.army.mil

Abstract – Given generalized requirements for a medium gain circularly polarized (CP) antenna we design and fabricate an axial mode helical antenna. This well known antenna has a relatively wide (1.7:1) bandwidth with gain proportional to the overall length. The antenna and ground plane diameters are determined by the chosen center frequency of operation. We evaluate the antenna design using FEKO electromagnetic simulation software for a center frequency of 700 MHz. We then fabricate one prototype with center metal rod support and foam core as in the conventional construction. We also desire a hollow core variant and use fiberglass to support the helical antenna. We present the measured results for these two types of construction compared to model results. Although the helical antenna embedded in fiberglass is a very rugged design it also involves sufficient dielectric loading to shift the antenna bandwidth to lower frequencies.

Index Terms– Helical antenna, circular polarization, fiberglass, Method of Moments, FEKO

I. INTRODUCTION

When circular polarization (CP) is required, the antenna designer has many choices, but for broadband applications a spiral or helical antenna structure often provides the best performance. A spiral antenna can be ultra-wideband whereas a helical antenna is typically limited to less than an octave bandwidth (1.7:1) [1]. We quantify the antenna impedance bandwidth (BW) in terms of the input reflection coefficient where the return loss is better than 10 dB while the realized gain BW depends on the application. Our objectives were for a 500 – 900 MHz right-handed CP (RHCP) antenna with 9 dBic average gain realized in the most compact size. To approach the gain requirement with a single antenna element we select a helix with axial length, L = 2 ft. We use the well known helix design procedure with a shaped metal ground plane although this does not address the effects of dielectric loading [1]. We model the helix using the FEKO electromagnetic simulation software[8]. We have modeled the dielectric structures using both the Method of Moments (MoM) surface equivalence principle (SEP), the thin dielectric sheet (TDS) and coated wire approximations in FEKO. We find only minor differences in results with these methods and use the hybrid finite element method (FEM) for uniform dielectrics without conductors. We summarize our findings using the coated wire approximation to represent the helix embedded in fiberglass and show results compared to measurements. The antenna is fed using a linear tapered 50 to 100 Ω microstrip transition 3-inch in length which is included in our refined model.

Once the basic design is complete we considered different fabrication options including foam, PVC pipe and a fiberglass tube on which to wind the helix. The conventional approach uses a foam core or dielectric rods to support the helical wire element. An axial mode helix is not very sensitive to metallic structures along the helical axis so that a metal support rod can be used. But this feature of the helical antenna may also allow other metal structures to be coaxially incorporated into the helical antenna. So we desire a hollow core helix that is still very rugged and use fiberglass sheets with polyester resin to encase the helical conductor. We describe the classical helix design and fabrication of the foam core and two fiberglass variants. The fiberglass thickness is non-uniform owing to the overlapping glass mat but is estimated at 1/16 – 1/6-inch when using 2 or

5 woven fiberglass mats to encase the ¼-inch diameter hollow copper tubing. We present measured results for these three prototype antennas compared to FEKO model predictions. By making assumptions about dielectric parameters we arrive at a model that can be validated with measurements to sufficient accuracy for engineering purposes.

II. ANTENNA DESIGN AND SIMULATION

The helical antenna design begins with the circumference, C, of the helical coils being chosen near the wavelength, λ_c, at the desired center frequency of operation. The coil diameter would be $D = \lambda_c/\pi$ = 5.37-inch for a center frequency of operation, f_c = 700 MHz. We chose a slightly larger diameter D = 5.56-inch, based on the outer diameter of a standard 5-inch PVC pipe as a convenient way to support the ¼-inch outside diameter copper tubing. The helix then has an impedance BW for wavelengths in the range $4/3C$ to $3/4C$ or 507 – 902 MHz. The classical helical antenna and design equations are well summarized in [1] where the example presented is very close to our desired frequency range. One important aspect for roughly uniform performance over the BW is the pitch angle $\alpha = \tan^{-1}(L/N\pi D)$ for N turns in the helical coil. Although the optimum α may be controversial [2], and tapered windings can be used, the typical choice is a constant pitch angle in the range, 12° – 15° [3]. Maintaining a constant or tapered pitch angle over the antenna length is one of the most difficult aspects of prototype fabrication.

Krauss provides an estimate for the helical antenna directivity $G \approx K_g \left(\frac{C}{\lambda}\right)^2 \frac{L}{\lambda}$, which includes a scale factor, $K_g \sim 15$, determined from empirical studies [3]. The half-power beamwidth (HPBW) of the radiation pattern is estimated according to $G(\mathrm{HPBW})^2 < 41250$ or HPBW ~ 43°. At the center frequency this provides an upper bound on the directivity G ~ 13.6 dBic but the data used were for $\alpha < 15°$. Based on the FEKO model results we chose a 5-turn helix with $\alpha = 15.4°$ having an axial length of 2 feet. We use a shaped ground plane where the minimum diameter is often chosen as $d_g = 0.8\lambda_c$ = 13.5-inch [1]. With FEKO we find only a small gain reduction using $d_g = 0.76\lambda_c$ = 12.75-inch which corresponds to the outer diameter of a 12-inch PVC pipe. Even though we choose to use thin fiberglass for this outer protective radome, we consider this a minimum diameter ground plane. The optimum height of the edge has been reported as $\lambda_c/4$ = 4.22-inch [1] and our FEKO model results support this choice. The ground plane size is chosen to be as small as possible without reducing the gain or pattern purity over the desired BW, although the front-to-back (F/B) ratio decreases with a smaller ground plane size. The model with the helix wound on 5-inch PVC pipe and an outer 12-inch PVC pipe to protect the antenna along with the thin fiberglass variant are shown in Fig. 1. We use hollow copper tubing with outer diameter ¼-inch to wind the helix since very thin wire can limit the antenna BW. The shaped (or cupped) ground plane improves the gain ~1 dB over the BW, which is about the same improvement that can be obtained by significantly increasing the ground plane diameter.

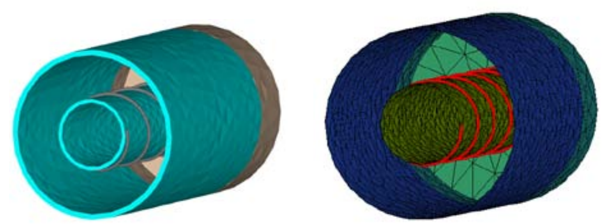

(a) (b)

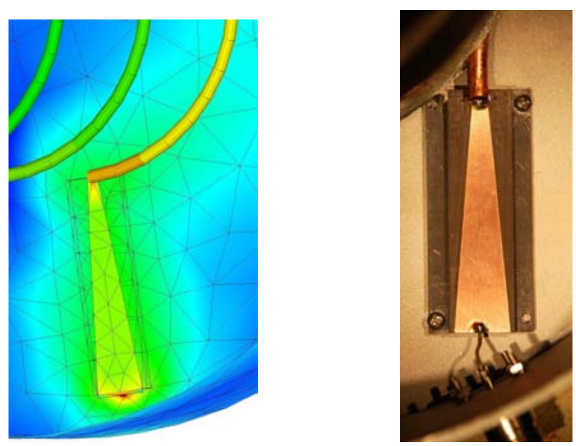
Fig. 1. The FEKO model for a helical antenna with shaped ground plane wound on (a) PVC pipe and (b) thin fiberglass forms.

The metal rod with foam core to support the helix has been previously described and is approximated in FEKO by including only the helical conductor and ground plane. We also modeled various materials to construct a hollow core structure including PVC pipe and thin fiberglass laminates, although the dielectric parameters used in the model are approximate. For a standard 5-inch PVC pipe thickness (0.26-inch) we used the SEP in FEKO compared to the TDS approximation with negligible differences. The large PVC thickness has an impact on performance (not shown) so we focus on fiberglass construction where the helical element is embedded during the lay-up process. With this construction the helical conductor is larger than the fiberglass thickness which would be difficult to model exactly. Comparing measurements for the helix wound on a foam core and embedded in fiberglass we observe a shift in the return loss and boresight gain to lower frequencies associated with the dielectric loading effects on the antenna, in addition to a high frequency gain reduction. We perform a parameter study of the fiberglass thickness and loss tangent because these parameters are not known exactly. They depend on the dielectric properties of the resin and the resin content in the cured structure. Based on this study we use a large dielectric loss tangent, tanδ = 0.1 and a thickness of 1/8-inch or 1/6-inch for which the results provide an upper and lower bound to the measurements. The actual loss tangent and thickness could be variable over the various cured fiberglass structures so that some approximations and assumptions are required to develop a practical model.

The coated wire approximation provides similar results as the TDS but is much more efficient taking about half the time for these simulations. So we use a coated wire to model the helix embedded in thin fiberglass having ε_r = 4.5 with loss tangent, tanδ = 0.1. The construction includes a nylon base as part of the cured fiberglass structure which is then bolted to the ground plane. The effect of the nylon base is less than that for the fiberglass since the dielectric loading effect of the nylon is only in the antenna feed region. We use the coated wire approximation to represent the helix embedded in thin fiberglass providing the most efficient simulation with the expected frequency dependence. This model includes the nylon base as a uniform dielectric volume having ε_r = 3.2 and tanδ = 0.1 solved by the hybrid finite element method (FEM) in FEKO. It includes the impedance transformer which is located in the approximate position of the prototype antennas and its substrate is also solved with the FEM. Model results are compared to measurements in terms of return loss, realized gain and axial ratio (AR) versus frequency. In all cases the helical element is wound for RHCP.

III. PROTOTYPE FABRICATION

We use a 50 to 100Ω microstrip transition to match the antenna to a 5Ω input. The des ign was developed using FEKO and artwork for fabrication was produced with LPKF CircuitCAM[9]. The 3-inch long linear tapered transition with a 1.25-inch wide bottom ground plane was fabricated with two layers of Rogers RT/Duroid 5870 using an LPKF 93s circuit board milling machine. The material for each layer is 125 mil thickness with single sided ½ ounce copper and has a relative dielectric constant, ε_r = 2.33 and loss tangent, tanδ = 0.0012. The two unclad sides were bonded together with 3M adhesive film [10]. The transmission line width tapers linearly from 669 mil (17 mm) to 158 mil (4 mm) with wire connection at one end and the helical element directly soldered to the opposite end. The FEKO model, with current at 700 MHz, and installed part are shown in Fig. 2.



(a) (b)

Fig. 2. Linear tapered microstrip impedance transformer (a) model and (b) as installed part.

We fabricated both the foam core and hollow core fiberglass structures in order to make measurements on both approaches for model validation. The ground plane is fabricated from cold-rolled Al with a welded lip. The foam core was supported by a 1.2-inch diameter metal rod on the centerline bolted to the cupped ground plane as shown in Fig. 3(a) during the antenna measurements. The helical element is simply glued to the foam support and soldered to the microstrip impedance transformer. This approach is low-cost and lightweight but the helical conductor is exposed and possibly prone to damage or changes in position which would reduce performance. The 2nd prototype used the same cupped ground plane but now the helical element is embedded in fiberglass as shown in Fig. 3(b). The cured structure includes a notched cylindrical nylon base 3-inch in height which is then bolted to the ground plane. The antenna element extends from the fiberglass to allow attachment to the microstrip transformer. Using 5-layers of fiberglass was very rugged but thicker than desired for minimal performance impact so we used only 2-layers for the thinnest structure that would still be reasonably rigid. The 2-layers of fiberglass have thickness about half the conductor diameter. The basic helical antenna design is straightforward and normally becomes an exercise in impedance matching to obtain wide band performance. In our case the dielectric loading complicates the design and the development of accurate models because the dielectric losses are difficult to estimate as a function of frequency.

(a)

(b)

Fig. 3. Helical antenna element (a) on foam core and (b) embedded in fiberglass.

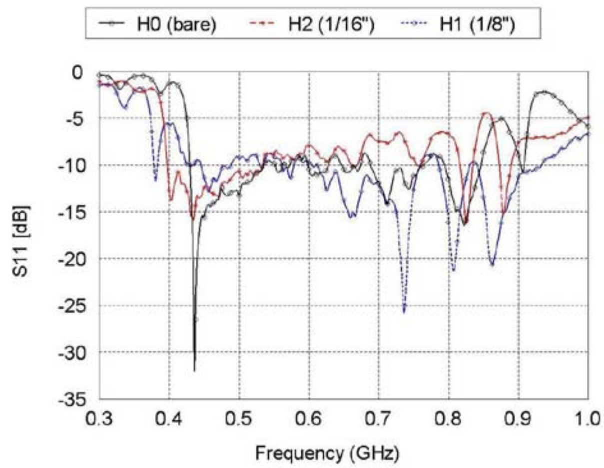
IV. ANTENNA MEASUREMENTS

The various prototype antennas were measured in the ARL tapered anechoic chamber [4, 5]. We used two Satimo SH400 [11] wide band dual-ridged horns as reference antennas. These horns have an impedance BW of 0.4 – 6 GHz with highly accurate performance data to provide a reference antenna with known gain as specified by the manufacture. With careful installation and laser alignment we obtain an accurate calibration over the entire frequency band of interest, 0.4 – 1 GHz. With the correct alignment of transmit and receive antenna boresight directions we can obtain a typical measurement error of ±0.25 dB for gain measurements. This assumes that the reference antennas are aligned and the reference gain is known accurately such that this source of error is negligible. We carefully calibrate every day and since the Satimo antenna gain has been well validated this is not a bad assumption. Positioning error of the antenna under test is the largest source of uncertainty and the large diameter of the helix antenna make this alignment more difficult. Based on repeat measurements we estimate a worst-case error of ±0.5 dB or 11% error. We measure the gain on the helix axis (or boresight) versus frequency so that relative to the reference measurement we can normalize our radiation pattern data to the measured gain at each frequency. Using a linearly polarized transmit antenna requires rotating the CP antenna under test about the helix axis to obtain a maximum in order to align the antenna polarization ellipse to the transmit antenna polarization. Then, we can rotate the test antenna $90^{o} \pm 0.1^{o}$ to obtain the orthogonal component. We collect azimuthal pattern data every 100 MHz in 1^{o} angular steps for both the major and minor axis of the circularly polarized antenna. The data can then be combined to obtain the RHCP gain and AR as a function of frequency and the RHCP radiation patterns. Since we combine two gain measurements which can have error in the boresight alignment we must accept a larger error of 15% in the RHCP gain and AR measurements. Thus we consider comparisons to model results to within this error of ±0.7 dB to be excellent agreement.

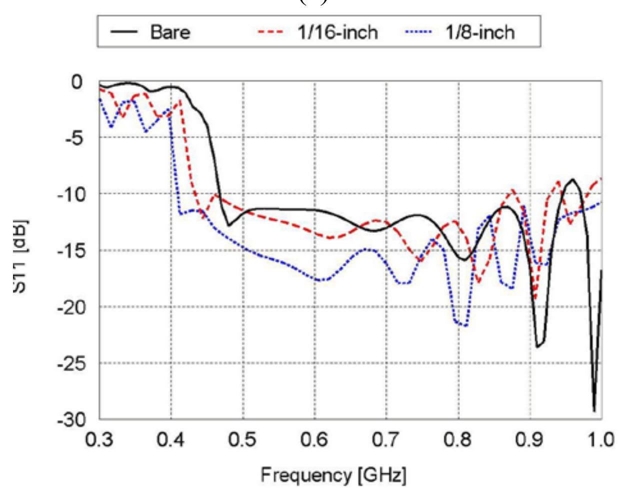
V. RESULTS

We compare model results and measurements for three different prototype antennas. The first is the foam core with metal rod support (H0). The others are fiberglass encasing the helical conductor with minimum thickness of approximately 1/8-inch (H1) or 1/16-inch (H2). The measured S_{11} for these three prototypes are compared in Fig. 4(a) with the FEKO model results shown in Fig. 4(b). Notice that the shift to lower frequencies with increasing fiberglass thickness is evident in the model results. But for input impedance the model is only approximate because the feed region connections are not modeled exactly. The input impedance is quite sensitive to the physical configuration of the 1st half turn of the helix and how the connector is attached. We attempt to transition the helical conductor smoothly from where it is attached directly to the microstrip transformer to following the desired pitch angle. The model results are better than 10 dB return loss over the entire 500 – 900 MHz BW whereas the prototype antennas have somewhat larger reflection co-efficient at some frequencies. The prototypes also have resonant peaks near 900 MHz that exceed the objective. The majority of these differences are due to the wire connection for the coaxial connector (see Fig. 2(b)). Although not shown, the results for the connector pin soldered directly to the microstrip transformer are much closer to predicted.

The RHCP gain on boresight versus frequency is shown in Fig. 5 for the thinnest fiberglass antenna compared to coated wire models with different thickness. The FEKO results are for the helix having 1/16 or 1/8-inch thick fiberglass coating where the maximum thickness for this electrically thin layer approximation is 1/6-inch. The model result for a 1/8-inch thickness is most similar to the measurement so the actual fiberglass construction is probably thicker than assumed but could also vary over the antenna length. None of our models predict the extended performance below about 450 MHz because the input impedance is not well predicted at these frequencies. However, the predicted frequency shift in the impedance bandwidth with increasing fiberglass thickness is consistent with measurements as can be seen in Fig. 4(a) but is less obvious in the realized gain versus frequency.



(a)



(b)

Fig. 4. (a) Measured S_{11} for three prototype helical antennas and (b) model results.

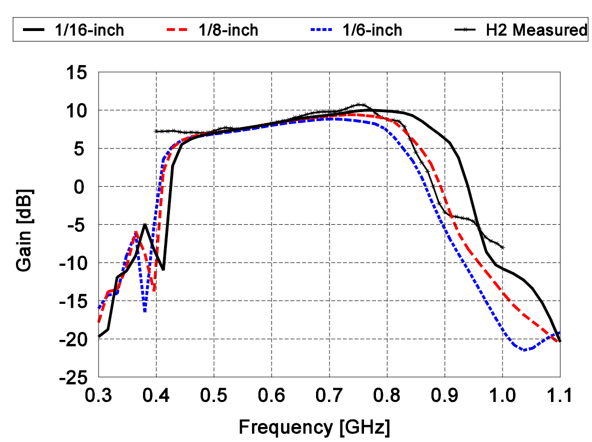


Fig. 5. The calculated versus measured RHCP realized gain on boresight for H2.

The boresight AR comparison (in linear space) is shown in Fig. 6 where in FEKO negative values represent left-handed CP (LHCP) whereas in our measurements LHCP is indicated by values larger than unity. As can be seen the antennas have excellent AR ~ 1 which would correspond to 0 dB. Our fiberglass model is either 1/16 or 1/6-inch thickness using the coated wire approximation which is valid at the frequencies of interest. The relative permittivity of fiberglass is typically ε_r = 4.5 but that for the resin or the cured combination (20 – 30% resin by volume) is uncertain. The loss tangent is more difficult to obtain for the polyester resin, but other researchers have found resin systems to have an imaginary part of the permittivity to be roughly flat with frequency at ε_r'' ~ 0.5 [6], so we use tanδ = 0.1.

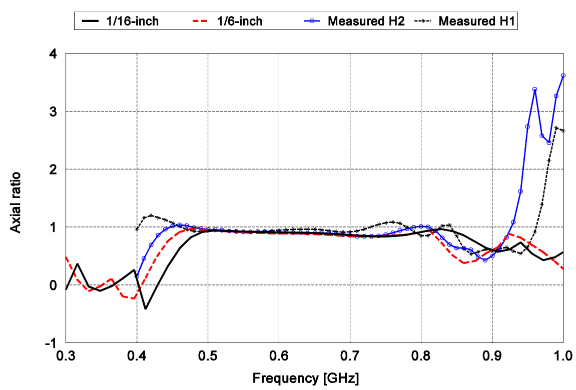
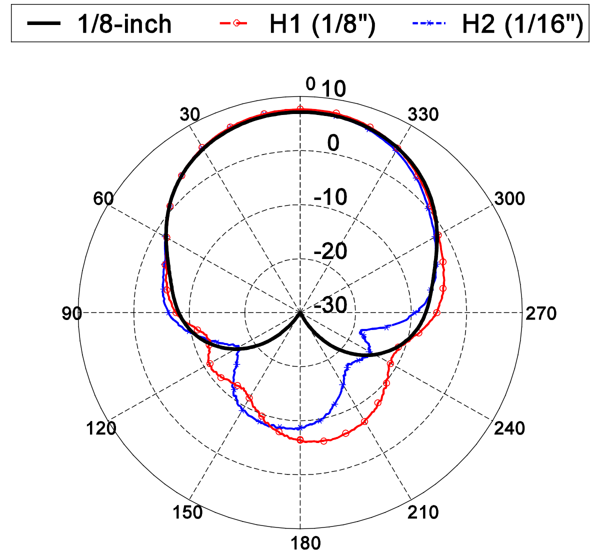
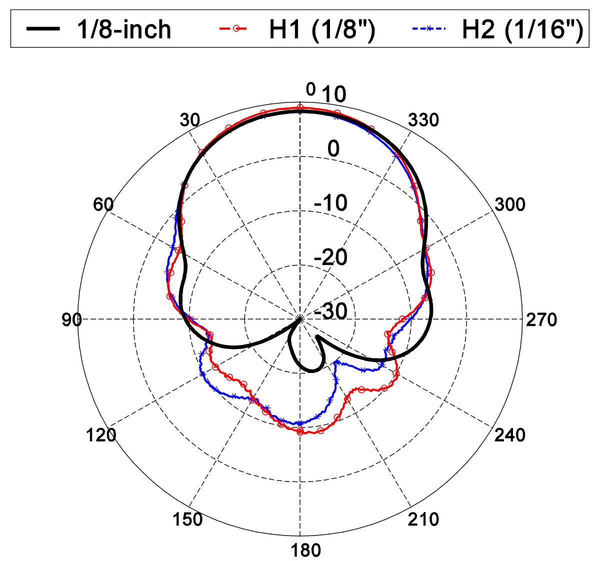


Fig. 6. The calculated versus measured AR on boresight for two prototype antennas.

Selected pattern measurements are compared to the model results for the helix with 1/8-inch thick fiberglass coating. The comparisons at 500 and 600 MHz are shown in Fig. 7 (a) and (b), respectively. The model agreement over the pattern beamwidth is excellent but the back lobes are not well predicted as is often the case in pattern comparisons [7]. Obviously there are more asymmetries in the as-fabricated prototypes than in the model which is typical since there is always some physical modeling error.



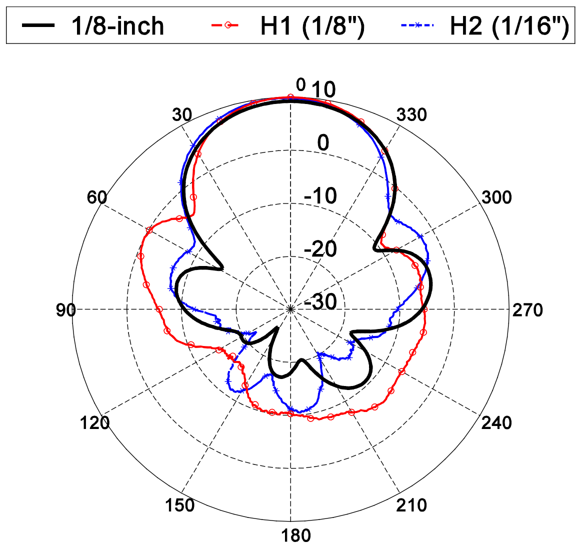
(a)



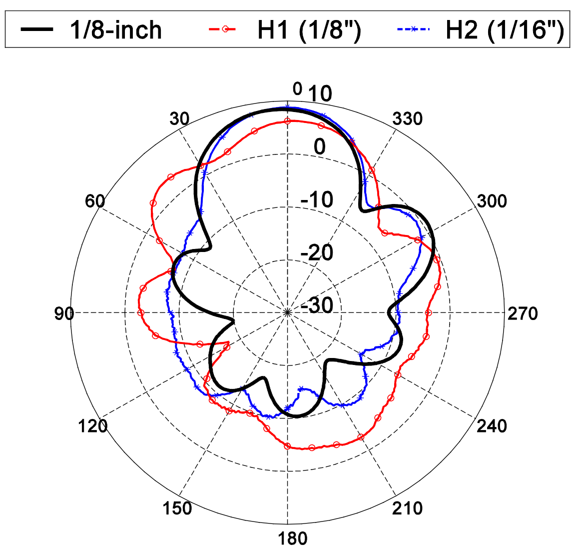
(b)

Fig. 7. Measured RHCP radiation patterns compared to model results at (a) 500 MHz and (b) 600 MHz.

The comparisons at 700 and 800 MHz are shown in Fig. 8 (a) and (b), respectively. The patterns at the band edges have off-boresight peak gain. At higher frequencies the helix radiation mode changes with a conical pattern [1]. In all cases the pattern comparison near boresight is excellent with differences on the order of the experimental error. At other angles the agreement is reasonable except in the back lobes. The FEKO model indicates that this choice of ground plane size is sufficient to obtain a good F/B ratio > 20 dB but this is not supported by the measurements.



(a)



(b)

Fig. 8. Measured RHCP radiation patterns compared to model results at (a) 700 MHz and (b) 800 MHz.

VI. CONCLUSIONS

The fiberglass prototype measurements have approximately the predicted shift in impedance bandwidth to lower frequencies with increasing fiberglass thickness. However, the data indicates a larger shift in the gain BW to lower frequencies than predicted although we did not make measurements below 400 MHz. The thicker fiberglass produces a larger shift in the gain and impedance BW with reduced gain at higher frequency. Our fiberglass model with $\varepsilon_r = 4.5$ and $\tan\delta = 0.1$ has this same trend but not to the same extent as measured. By increasing the thickness we obtain better agreement which implies that the fiberglass thickness can be used as a design parameter. That is, the basic helix can be designed to operate at a higher frequency than desired expecting the dielectric loading to shift the antenna frequency response. In the range where the gain remains roughly constant versus frequency, the radiation patterns are stable and have excellent AR. The measured forward patterns for the fiberglass prototypes compared to the model results are in good agreement in this frequency range. Although a larger error is possible when measuring the antenna backlobes, the discrepancies in this part of the pattern comparisons are larger than expected so that the model results can be misleading if the F/B ratio is a concern. For the fiberglass construction the patterns become corrupt around 800 MHz with reduced gain and AR. The as-fabricated helical antennas cannot be modeled exactly but the numerical model provides the correct frequency trends. In order to meet our BW objectives the helix would have to be redesigned accounting for the dielectric loading effects. Thus a smaller diameter helix would be used to shift the antenna performance to higher frequencies and the relatively larger ground plane size may improve the F/B ratio. Although the modeling uncertainties reduce the model accuracy, the model is sufficient for engineering analysis and provides a baseline for model refinement and optimization.

REFERENCES

[1] H. E. King, J. L. Wong, and E.H. Newman, "Helical Antennas," *Antenna Engineering Handbook*, 4th Ed., J. L. Volakis (ed.), Chap. 12, New York: McGraw-Hill, 2007.

[2] A. R. Djordjevic, A. G. Zajic, M. M. Ilic and G. L. Stuber, "Optimization of Helical Antennas," *IEEE Antennas and Propagation Magazine*, vol. 48, no. 6, pp. 107 – 115, Dec. 2006.

[3] J. D. Kraus, "The Helical Antenna," *Antennas*, Chap. 7 (New York: McGraw-Hill, 1950).
[4] S. Weiss and A. Leshchyshyn, "Anechoic Chamber Upgrade," Army Armament Research, Development and Engineering Center, ARAED-TR-95009, May 1995.
[5] "Free Space VSWR Test for Tapered Anechoic Chamber," Advanced Testing Services, 13116-TR-VSWR, January 2009.
[6] R. B. Bossoli, "The Microwave Permittivity of Two Sprayable Resin Systems," U.S. Army Research Laboratory, ARL-TR-3907, September 2006.
[7] W. O. Coburn and C. Fazi, A Lumped Circuit Model for a Tri-Band Trapped Dipole Array– Part 2: Stacked Arrays, *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 648 – 651, 2008.
[8] EM Software and Systems, "FEKO", *www.feko.info*.
[9] LPKF Laser and Electronics, "LPKF CircuitCAM", *www.lpkfusa.com*.
[10]3M, "3M adhesive film", *www.3m.com*.
[11]Satimo, "Satimo SH400", *www.satimo.com*.

William O'Keefe Coburn received his BS in Physics from Virginia Polytechnic Institute in 1984. He received an MSEE in Electro physics in 1991 and Doctor of Science in Electromagnetic Engineering from George Washington University (GWU) in 2005. He has 28 years experience as an electronics engineer at the Army Research Laboratory (formerly the Harry Diamond Laboratories) primarily in the area of CEM for EMP coupling/hardening, HPM and target signatures. He currently is in the RF Electronics Division of the Sensors and Electron Devices Directorate applying CEM tools for antenna design and analysis.

Canh Ly received the Bachelor of Science degree in Electrical Engineering from the University of Maryland, College Park, MD, the Master of Science degree in Electrical Engineering from the Johns Hopkins University, and the Ph.D. degree in Information Technology from the George Mason University. Dr. Ly has been Member of Technical Staff at U.S. Army Research Laboratory (ARL). He has submitted three patents related to frequency estimation technique, patch array antennas, and published papers in IEEE Radar Conference Proceedings, Asilomar Conference, and SPIE Conference. His research interests include antenna design, advanced HEMP techniques, superresolution algorithms for millimeter wave (MMW) radars, statistical signal processing, and radar array processing.

Timothy A. Burcham has been a member of the US Army research and testing community for over twenty years providing engineering design and technical expertise to many military programs. He has been involved in many novel experiments for agencies such as DARPA and Army weather command.

Russel Harris worked for the past 27 years at the US Army Research Laboratory doing digital design, programming and printed circuit board design. Received a B.S. in Microbiology from the University of Maryland in 1973 and worked as a support scientist for the USDA in plant pathology until 1982.

Amid M. Bamba is an undergraduate student of Electrical Engineering at Morgan State University. His research interests include investigating and testing the electromagnetic behavior of antennas.