Investigations on a Novel without Balun Modified Archimedean Spiral Antenna with Circularly Polarized Radiation Patterns

Balamurugan Shanmugam, and Satish K. Sharma

Department of Electrical and Computer Engineering
San Diego State University, 5500 Campanile Drive, San Diego, CA, USA, 92182-1309
Email: sbalamurugan9587@gmail.com and ssharma@mail.sdsu.edu

Abstract **─** The proposed novel modified two-layered Archimedean spiral (Mod Arspl) antenna achieves a simple feed without balun and maintains the antenna input impedance close to 50 Ω over extremely wide (10:1) frequency band for antenna design. It shows excellent impedance matching, higher peak gain and acceptable axial ratio over the operating frequencies compared to the conventional Archimedean spiral geometry on two-layers with the same aperture area. The working of this antenna and important design parameters to achieve frequency independent response with respect to matching and CP radiation patterns are discussed. The best case with free-space Mod Arspl has impedance BW (S_{11} < -10 dB) of 3.2-19.2 GHz (6:1 band), AR BW (AR < 3dB) of 3-20 GHz (6.6:1 band), stable broadside gain of 4-5.5 dBic and quasi-axial patterns in the usable 6:1 band. Radiation patterns show some beam squint towards higher frequency end attributed to spacing between the two layers of the spiral arms. The fabricated prototype antenna using microwave substrate shows CP operating BW over 5.21:1 frequency band (2.8 - 14.6 GHz) and peak gain varying between 4 - 8 dBic in this frequency band. Measured results show reasonable agreement with the simulated ones.

Index Terms **─** Archimedean spiral antenna, circular polarization, modified spiral antenna, two-layered spiral, without Balun spiral antenna.

I. INTRODUCTION

Frequency Independent characteristics of a Archimedean spiral (Arspl) antenna invented by J.A. Kaiser in 1960 are well known [1], [2] and explained qualitatively by radiating ring theory. Planar spiral antennas, being a self-complementary structure, have the real impedance of 188 Ω given by Mushiake equation in [3]. This necessitates the use of baluns for balanced-mode operation. Baluns limit the inherent frequency independent operation of spiral antennas and also increases the complexity. In [4] the authors eliminate the balun by employing a single arm spiral with disc/ground plane which has comparable performance with the two-arm spiral fed with balun except for the beam asymmetry and squint. In [5], the authors eliminate balun by reverting to unbalanced mode excitation with one of the spiral arms as a parasitic element. In [6] the authors propose a stripline fed Archimedean spiral by having a broadband impedance matching network conformal to spiral's windings to transform the input impedance of two-layered spiral to the impedance of stripline over 10:1 band. Although, not the focus of this paper, cavity backing for the proposed antenna was also implemented to achieve directional radiation patterns such as in in [7-8]. Similarly, the effect of dielectric loading, as reported in [9-10] was also performed, but not discussed here.

This paper investigates a two layered Archimedean spiral antenna which will be suitable for feeding with a 50 Ω coaxial line considering free space or foam substrate. The two-layered geometry with conventional Archimedean spiral design (referred as Arspl in this paper) is compared with the proposed two-layered geometry with modified Archimedean spiral design (referred as Mod Arspl) with the goal being the frequency independent response in terms of impedance matching, circular polarization (CP) at broadside angle and stable pattern with a balun-free coax

Submitted On: March 22, 2012
Accepted On: July 26, 2012

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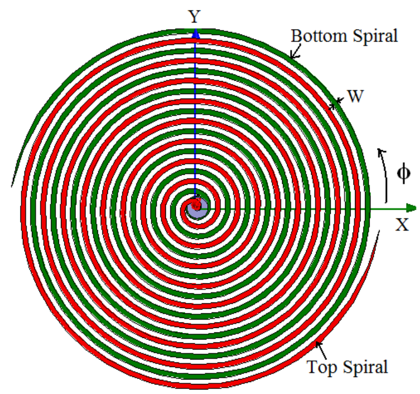
excitation. Some preliminary investigation results of this antenna were presented in [11], and therefore, are not included here, for the sake of brevity. Since the proposed Arspl does not need a wideband balun or is quite simple to excite by a 50 Ohm SMA connector alone, hence it offers low cost and light weight implementation while still providing acceptable antenna performance. This can be acceptable for several communication applications, even if with some compromise in quality of the CP patterns.

Section I describes the configuration of Mod Arspl and compares its performance with the Arspl of the same diameter. The working of Mod Arspl is also explained. Section II discusses the important design parameters for achieving matching and stable CP radiation patterns. Section III presents the experimental results of Mod Arspl. Important findings are summarized in the conclusions section. The simulations are generated using Ansoft Corporations High Frequency Structure Simulator (HFSS) v12 which is a finite element method based full wave analysis tool.

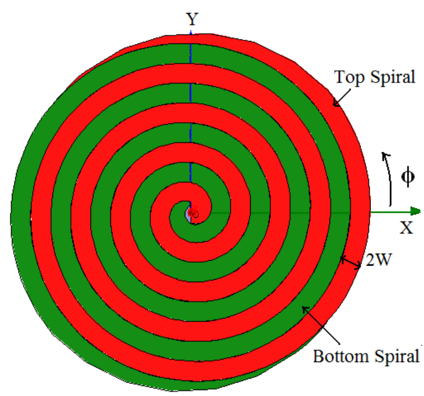
II. MODIFIED ARSPL COMPARED TO CONVENTIONAL ARSPL

The top view of conventional two layered Arspl is shown in Fig. 1(a) whose configuration parameters are given in Table 1. The top spiral arms is at a height h from the bottom spiral as shown in Fig. 1(c) fed-in with a 50 Ω coaxial SMA connector. There is foam substrate (ε_r=1.06, tan δ=0.002) between the two spiral arms which is realizing the free space design. The radial distance from the center to any point on the arm is defined by the Archimedean function $r = a_{sp}\Phi_w$ where a_{sp} is the spiral constant and Φ_w is the winding angle varying between the starting angle Φ_{st} and ending angle Φ_{end}. The diameter of the spiral D is defined by $D = 2r_{max}$ with $r_{max}= a_{sp}\Phi_{end}$. The two layered Mod Arspl has double the arm width that of the Arspl and its top view is shown in Fig. 1(b). This modified geometry will create a short circuit or single conductor sheet if the spiral arms are kept at the same level. Its configuration parameters are given in Table I. The arm widths of Arspl and Mod Arspl are denoted as W and AW, respectively, with $AW = 2W$. The Mod Arspl has twice the growth rate or spiral constant (a_{sp}) and half the number of turns (N) as that of Arspl so that the aperture areas of both antennas remain the same.

The spiral arms of both the antennas are tapered at the ends to minimize the reflected current towards the feed. In case of Arspl, there are top and bottom circular stubs of diameter 1.2 mm and 4.8 mm, respectively, connecting the spiral arms to the SMA. Feed portion of Arspl is zoomed to show the top circular stub of 1.2 mm diameter (Fig. 1(c)). In comparison to this, the Mod Arspl has only a bottom stub of diameter 6.4 mm. A top circular stub of diameter 1.2 mm is used when the arm width of Arspl and Mod Arspl is less than or equal to 2 mm. Feed portion of Mod Arspl is zoomed in Fig. 1(d) to show the SMA feed and the circular stub of diameter 6.4 mm attached with the bottom spiral.



(a)



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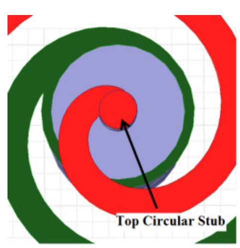
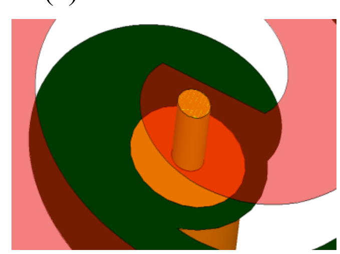
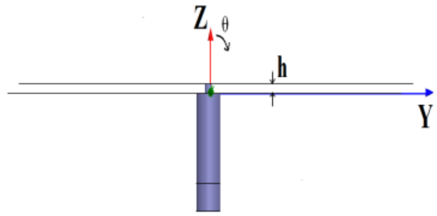


(c)



(d)



(e)

Fig. 1. Conventional and modified, two layered, Arspls (a) Top view of Arspl, (b) Top view of modified Arspl, (c) Feed portion of Arspl zoomed to show the top circular stub of 1.2 mm diameter, (d) Feed portion of Mod Arspl zoomed to show the SMA feed and the circular stub of diameter 6.4 mm attached with the bottom spiral, and (e) Side view of both Arspl and Mod Arspl.

Table 1**:** Antenna design parameters of the conventional and modified Archimedean spirals

Symbol	**Arspl**	**Mod Arspl**
Arm width	$W = 2$ mm	$AW = 4$ mm
h	1 mm	1 mm
a_{sp}	0.63 mm/rad	0.63 x 2 mm/rad
Φ_{st}	0.5π rad	0.5π rad
Φ_{end}	18.47π rad	18.47π/2 rad
N	9	4.5
D	73.1 mm	73.1 mm

The input impedance of conventional Arspl and Mod Arspl, both two layered, are plotted in Fig. 2. It can be inferred that the resistance (R_{in}) of Arspl varies between 25 - 150 Ω whereas for the Mod Arspl, it varies between 30 - 80 Ω which can be easily matched to a 50 Ω line. Also the input reactance X_{in} of the Mod Arspl is less oscillatory compared to the Arspl. The reason for this trend is explained in the next paragraph.

According to [3], a Self-Complementary Antenna (SCA) is one which leaves the geometry unchanged when the metal and blank spaces in a planar antenna are interchanged except for a rotation equal to one-half of its angular periodicity. Mushiake in [3] describes about both the planar (2D) as well as 3D self-complementary structures and their input impedance properties. Any self-complementary structure (2D or 3D) has a constant input impedance which is independent of frequency [3]. Theoretically, planar SCA have a constant input impedance of $Z_0/2$ (i.e. 188 Ω) and the planar two-arm conventional Archimedean spiral that is well known for the last 50 years is one such antenna. In trying to achieve a simple feed, the two layered design explored in this paper disturbs their planar SCA nature and the problem is now shifted to 3D which means that the Arspl will not have a constant impedance of around 170 Ω (Arspl has 25% of its area covered by metal on both top and bottom layer and its complement will have 75% of top and bottom layers covered by metal which is clearly not a SCA).

Therefore, the proposed Mod Arspl (Fig. 1(b)) is a 3D self complementary antenna with 50% of the area covered by metal on both top and bottom layers which makes its complement have the same 50% area covered by metal on both top and bottom but with a of rotation of 180^0. Here, the top and bottom spirals are 2D self-complementary structures by themselves and the antenna can be considered as two stacked 2D self-complementary structures with the impedance of each point of the structure given by 60π Ω as explained by [3]. Such a parallel arrangement of 2D structures each with 170 Ω impedance brings down the effective input impedance of the antenna to around 80 Ω (This is similar concept of having 2 parallel resistors of R ohms each which makes the total resistance R/2). This explains the input impedance of the Mod Arspl being fairly constant over frequency but at a lower value (average of around 55 Ω) compared to the 188 Ω for planar self-complementary structures. Fig. 3 shows the reflection coefficient magnitude versus frequency for the conventional two layered Arspl and the proposed Mod Arspl which shows a distinct improvement with the modified geometry and its reflection coefficient magnitude is better than -10 dB from 2-20 GHz w.r.t. a 50 Ω coaxial line.

The axial ratio (AR) at broadside angle ($\theta=0^o$) is plotted for both the antennas in Fig. 4 which shows that the axial ratio of the Mod Arspl is worse compared to Arspl at lower end of the band (2-4 GHz) due to the number of turns being halved which reduces coupling between the arms. This effect is seen throughout the band in the form of slightly increased AR and becomes more pronounced at the lower frequency end. The peak gain of both the antennas are plotted in Fig. 5

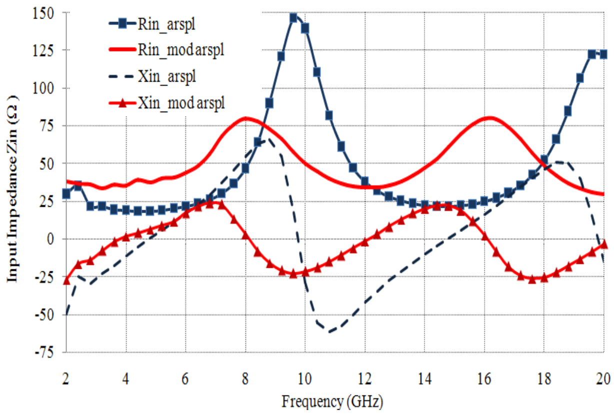


Fig. 2. Input impedance of Arspl and Mod Arspl.

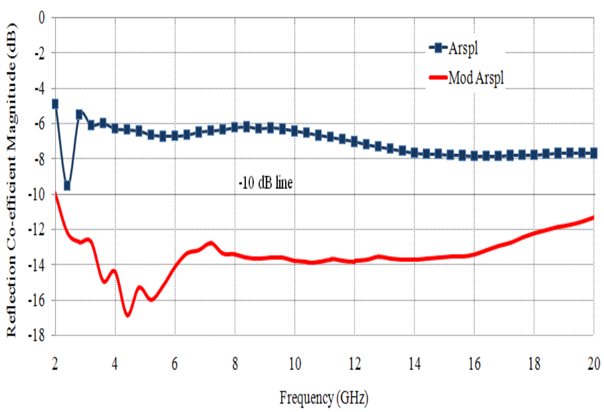


Fig. 3. Reflection coefficient magnitude versus frequency for Arspl and Mod Arspl.

which shows that the Mod Arspl has higher gain throughout the band.This increased gain can be partly attributed to the better impedance matching achieved and partly to the increased usage of metal instead of blank spaces (100% area covered with metal when seen from top instead of 50% in case of Arspl). This is a desired phenomenon since it partially achieves the purpose of cavity backing without increasing the antenna volume. The simulated left hand circular polarization (LHCP) and right hand circular polarization (RHCP) patterns of the Arspl and Mod Arspl are compared at different frequencies across the 2-20 GHz band in [6] and hence it is omitted here for the sake of brevity.

III. ANTENNA DESIGN PARAMETERS

Arm length is the length between the feed point and the arm end. The lower cut-off frequency for operating the spiral antennas as a CP antenna is denoted as f_L and upper cut-off frequency as f_U with the corresponding electrical wavelengths denoted as λ_L and λ_U. λ_g refers to guided wavelength. A spiral antenna radiates efficiently from a ring one wavelength in circumference according to band theory.

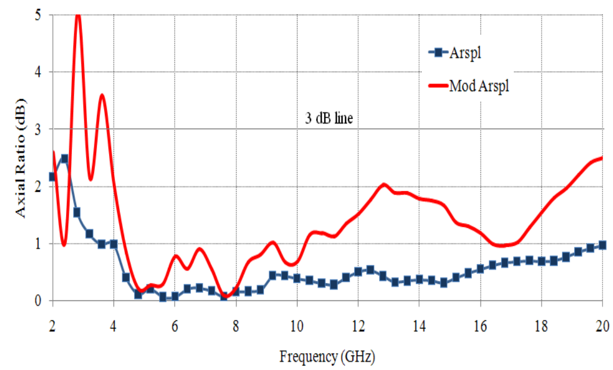


Fig. 4. Broadside axial ratio versus frequency for Arspl and Mod Arspl.

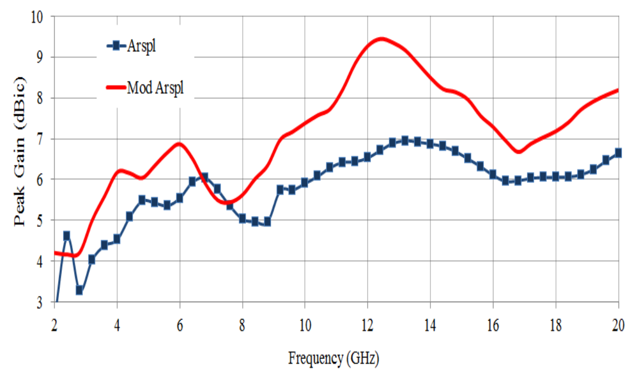
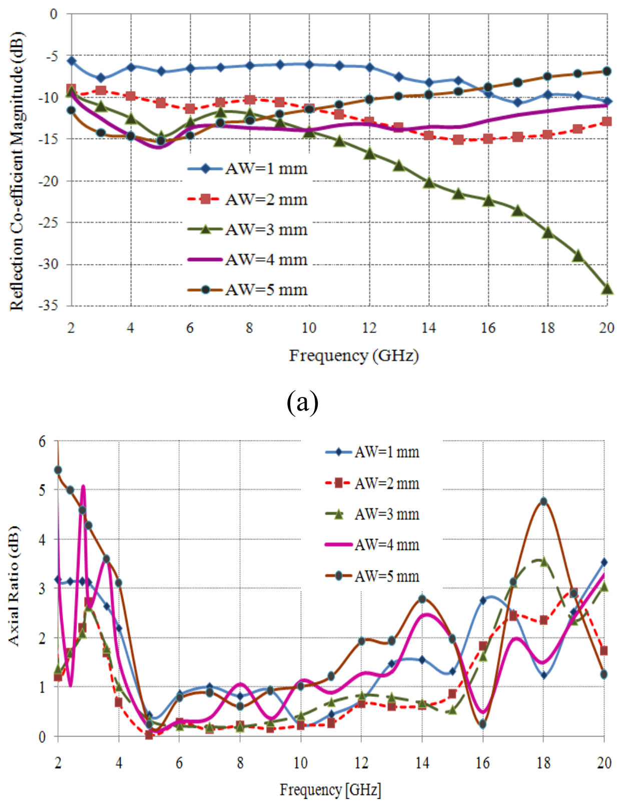


Fig. 5. Peak gain versus frequency for Arspl and Mod Arspl.

The conventional single layered spirals are designed to have a circumference equal to the desired λ_L. Most of the spiral designs reported in literature and also the commercial versions available exhibit better than 3-dB AR if the circumference of the spiral is atleast equal to one guided wavelength at the frequency of interest. These designs mostly have an arm width ranging from 0.5-2 mm which ensures that there are enough turns (and hence enough arm length of at least $4*\lambda_L$) within the same one wavelength circumference to create stronger coupling between the spiral arms thereby radiating most of the input energy as CP wave before it reaches the arm ends. The Mod Arspl constructed by doubling the arm width and halving the number of turns (compared to Arspl) within the same diameter is different in that aspect. Meeting the circumference requirement alone does not guarantee a CP radiation at that frequency and it requires a arm length of atleast (5-6)*λ_g as the current distribution is different from that of Arspl. Arm length depends on the number of turns N which inturn depends on the arm width *AW*. Arm length is the most important parameter that sets the lower cut-off frequency for the operation of Mod Arspl as a CP antenna.

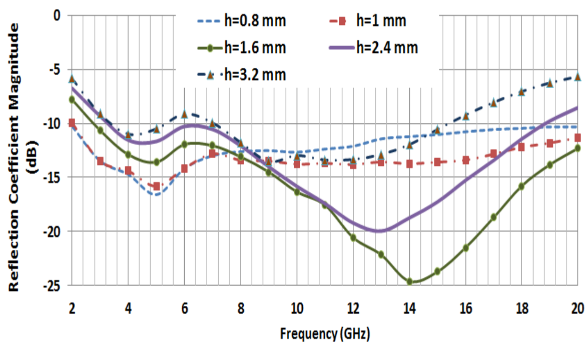


(b)

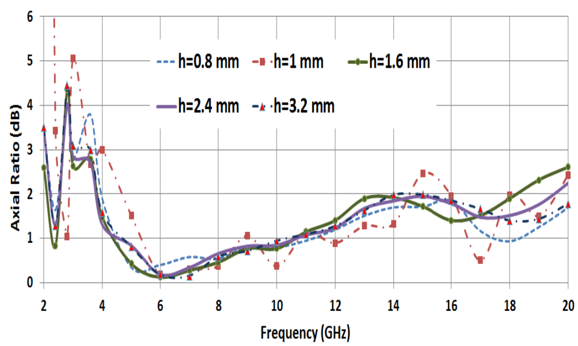
Fig. 6. Parametric studies showing the effect of *AW* on (a) reflection coefficient magnitude, and (b) broadside axial ratio.

Figure 6(a-b) shows the trend in impedance matching and axial ratio at broadside angle for varying the *AW* with h = 1 mm and D = 73.1 mm, respectively. Arm width equal or greater than 2 mm is recommended for these Mod Arspl designs as the smaller trace widths increase the antenna input impedance making it harder to match with SMA feed as it can be seen in the case of 1 mm *AW* in Fig. 6(a) showing poor impedance matching and a AR of greater than 3-dB at 3.5 GHz even with a arm length of 1920 mm. The impedance matching improves at low band (2-6 GHz) when the *AW* is increased from 1 to 5 mm but the higher frequenices (>12 GHz) are affected for *AW*>4 mm as seen in the 5 mm *AW* case. From Fig. 6(b), it can be inferred that the AR deteriorates at the low band till 4 GHz as the AW increases from 1 to 5 mm due to the decrease in arm length from 1920 mm to 340 mm. The AR BW starts from around 4 GHz for 4 and 5 mm AW as the arm length is 480 and 340 mm, respectively which is (5-6)*λg at 4 GHz. It can also be seen that 2 and 3 mm AW has an arm length of 960 (6.4*λg) and 720 mm (4.8*λg), respectively at 2 GHz which explains the AR BW starting before 2 GHz for these cases. For frequency independent antennas, only the lower cut-off frequency for AR BW is discussed because of the finite antenna geometry and the upper cut-off frequency depends on the accuracy of feed fabrication. In case of Mod Arspl, all the cases shown in Fig. 6(b) have an AR BW varying between 4:1 frequency band (*AW*=5 mm) and 10:1 frequency band (*AW*=2 mm). Ideally, a balun fed single layered spiral will have the impedance and AR BW starting from 1.4 GHz for a diameter of 73 mm. Based on the above discussion, the optimum arm width to operate the Mod Arspl will be from 2-3 mm which ensures that there is enough arm length to achieve CP at low band (2-4 GHz) and also maintain the impedance matching at these frequencies.

Though *AW* of 2-3 mm is the optimum, the level of impedance matching achieved throughout the 2-20 GHz band with 4 mm *AW* case compelled the authors to study the effect of height h with *AW*=4 mm which has AR BW from 4-20 GHz. A discussion of important parameter (h - separation of spiral arms) that affects the pattern quality is discussed in the coming paragraphs and Fig. 8. The impedance matching, axial ratio at broadside angle and CP gain at broadside angle for different cases varying the height h from 0.8-3.2 mm with *AW*=4 mm and D=73.1 mm are shown in Fig. 7(a-c), respectively. The AR BW remains fairly constant for all the cases (Fig. 7(b)) but the impedance BW reduces from 10:1 to 5:1 frequency band as the height is increased from 0.8-3.2 mm (Fig. 7(a)). This is due to the added inductance of the probe with increasing height of the center pin between the two spirals that lowers the matching level and therefore a maximum height of 3.2 mm is recommended.



(a)



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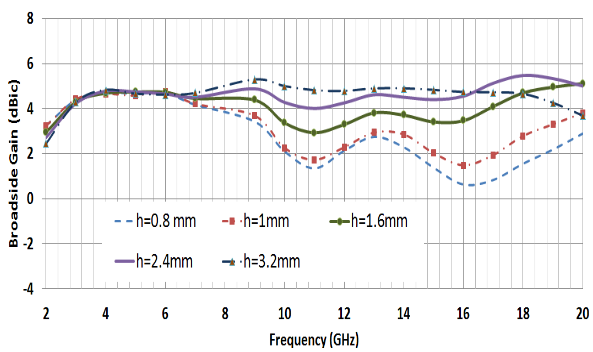


(c)

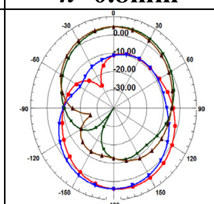
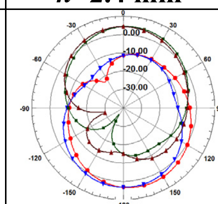
Fig. 7. Parametric studies showing the effect of *h* when *AW*=4mm and *D*=73.1mm on (a) reflection coefficient magnitude, (b) axial ratio at broadside angle, and (c) CP gain at broadside angle.

The most notable effect of increasing the separation between the spiral arms can be found in Fig. 7(c) which shows that the CP gain at broadside angle stays constant around 4-5 dBic from 3-18 GHz with increased spacing (*h*=2.4 and 3.2 mm) whereas for smaller spacing (*h*=0.8, 1, 1.6 mm cases) the broadside gain drops with increasing frequency.

The above perfromance can be explained from the radiation patterns plotted at different frequencies across the 3-18 GHz band in Fig. 8 for *h*=0.8 mm and 2.4 mm cases which show that the magnitude of back radiation is reduced throughout the band with *h*=2.4 mm case and the beam is pushed to the front, thereby, increasing the broadside gain at all frequencies. The bottom spiral and its stub acts as a partial reflector pushing the beam towards broadside angle if the spacing between the spirals is greater than 0.02λ. The broadside gain is therefore held constant even though the beam peak is not exactly at broadside angle. Note that the patterns of *h*=2.4 mm case are usable from 3-18 GHz as shown in Fig. 8. A spacing of 1.6-3.2 mm is recommended to achieve a frequency independent response with respect to impedance matching and gain at broadside angle for Mod Arspl. The pattern asymmetry and squint is solely due to the spiral arms being kept at different levels. Based on the above discussion, it can be concluded that the arm width and spiral diameter determines the AR BW whereas the impedance BW and pattern/gain stability depends on the spacing between the spiral arms. The best case with *AW*=4 mm, *h*=2.4 mm and *D*=73.1 mm has an impedance BW of 3.2-19.2 GHz (6:1 band), AR BW of 3-20 GHz (6.6:1 band), stable gain of 4-5.5 dBic at broadside angle with usable quasi-axial patterns throughout the 6:1 band.

IV. MOD ARSPL - EXPERIMENTAL VERIFICATION

The simulation results presented in the previous sections are based on using the foam substrate, which require hand fabrication. This method is prone to fabrication errors because it involves curved configuration. Considering this and to provide further practical significance to the spiral design, the Mod Arspl was redesigned on a low loss Rogers 5880 (ε_r = 2.2) substrate material and consequently, fabricated using a LPKF CAD milling machine which ensures fabrication accuracy.

Freq	*h*=0.8mm	*h*=2.4 mm
3 GHz Gain LHCP Phi=0 Gain LHCP Phi=90 Gain RHCP Phi=0 Gain RHCP Phi=90		

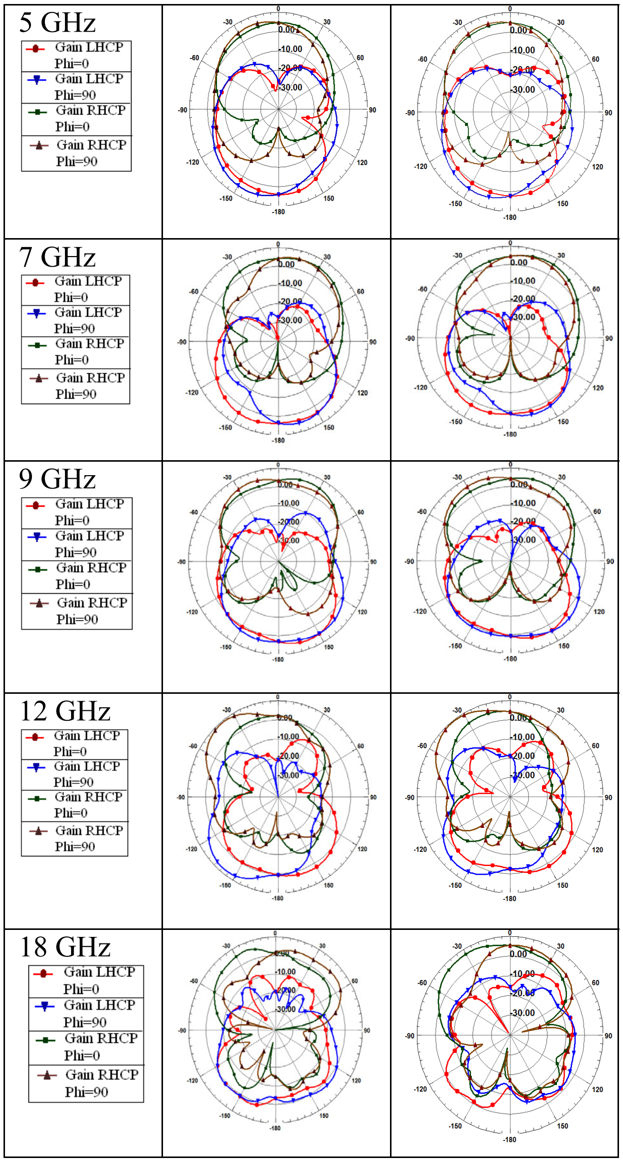
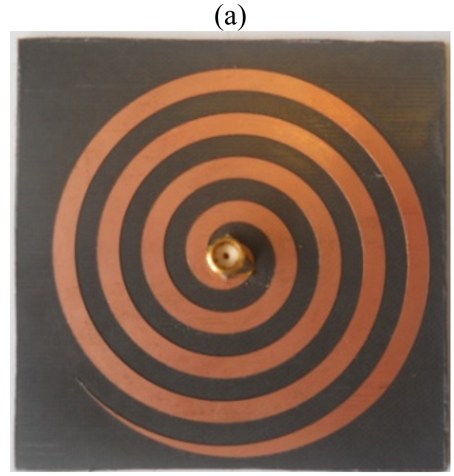


Fig. 8. Comparison of radiation patterns for cases *h*=0.8 and 2.4 mm to show the effect of reduced back radiation as the arm separation increases.

The parameters of the fabricated spiral are $AW = 4$ mm, $h = 1.6$ mm, $D = 73.1$ mm. The substrate is square shaped instead of circular shape used in the previous sections as shown in the photograph of fabricated prototype antenna in Fig. 9 which has the total dimensions 77 x 77 x 1.6 mm^3. The antenna is experimentally verified in the Antenna and Microwave Lab (AML) at SDSU which are also compared with the corresponding simulated data. The VSWR and broadside axial ratio are plotted versus frequency for the simulated and measured data in Fig. 10(a-b), respectively.

(a)

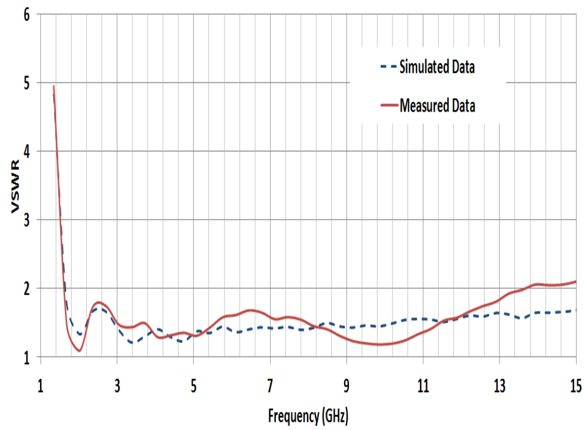


(b)

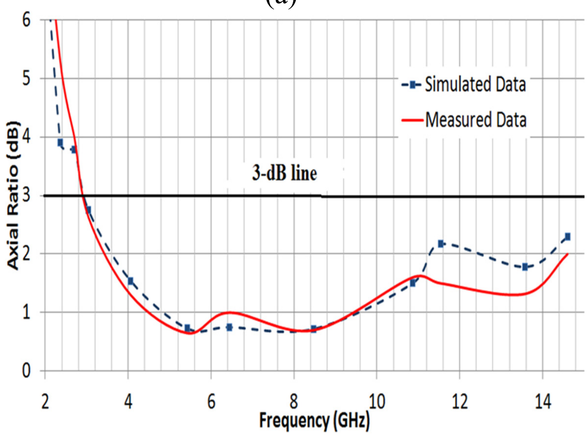
Fig. 9. Photograph of the fabricated prototype of Mod Arspl using the microwave substrate (a) top view, and (b) antenna as seen from bottom showing SMA feed.

The measured and simulated impedance BWs are from 1.6 to almost 15 GHz (frequency ratio = 9.375:1) as shown in Fig. 10(a). The measured AR, gain and patterns are obtained from analysis software purchased from Orbit/FR which computes the AR and radiation patterns from the measured linear patterns. The measured and simulated AR BWs are from 2.8 to 14.6 GHz (frequency ratio = 5.21:1) as shown in Fig. 10(b). The usable BW is defined as the common frequency range between the impedance and AR BWs which is also from 2.8 to 14.6 GHz (frequency ratio = 5.21:1 band). The simulated and measured LHCP and RHCP radiation patterns at different frequencies over the band are shown in Fig. 11 for $\phi = 0^o$, and 90^o cut planes. It can be observed that as frequency approaches the higher end, the patterns show some beam scan.

The measured and simulated CP peak gain varies from around 4 - 8 dBic in the usable band.



(a)



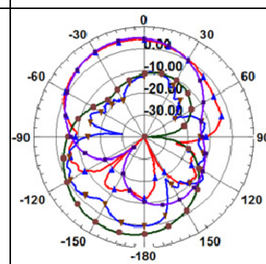
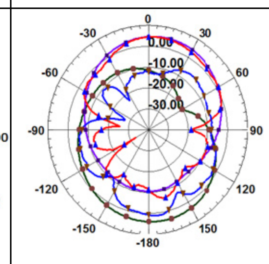
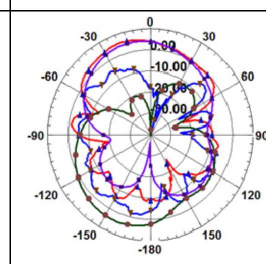
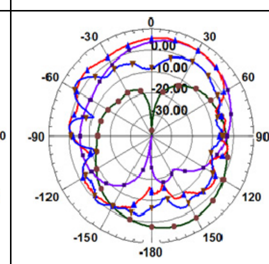
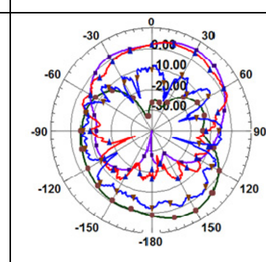
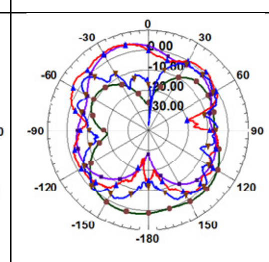
(b)

Fig. 10. Simulated and measured frequency response of a) VSWR, b) Axial ratio at broadside angle for the Mod Arspl on the microwave substrate.

It should be noted that the free-space based design discussed in the previous section offers over 6:1 usable band but the fabricated design on Rogers 5880 substrate with the same design parameters (only exception being the usage of 1.6 mm substrate thickness instead of 2.4 mm thickness) does not show same superior performance because the design parameters are not re-optimized on Rogers 5880.

V. CONCLUSIONS

This paper presented a novel antenna geometry called the modified two-layered Archimedean spiral antenna (Mod Arspl) with simple SMA feed without balun which shows improved performance in impedance matching and peak gain with a slight compromise in axial ratio BW compared to the two-layered design of the conventional Archimedean spiral (Arspl) geometry with the same aperture area. The best case with free-space or foam based Mod Arspl has impedance BW of 3.2-19.2 GHz (6:1 band), AR BW of 3-20 GHz (6.6:1 band), and broadside gain of 4-5.5 dBic in the usable 6:1 band. Radiation patterns show some beam squint as higher frequency end is approached which is attributed to the spacing *h*. The fabricated prototype on a microwave substrate has CP usable band from 2.8 - 14.6 GHz (5.21:1 band) with peak gain varying between 4-8 dBic. Measured results show reasonable agreement with the simulated ones.

Freq (GHz)	Phi=0 deg Simulated RHCP Measured RHCP Simulated LHCP Measured LHCP	Phi=90 deg Simulated RHCP Measured RHCP Simulated LHCP Measured LHCP
3.04 GHz		
5.08 GHz		
7.46 GHz		

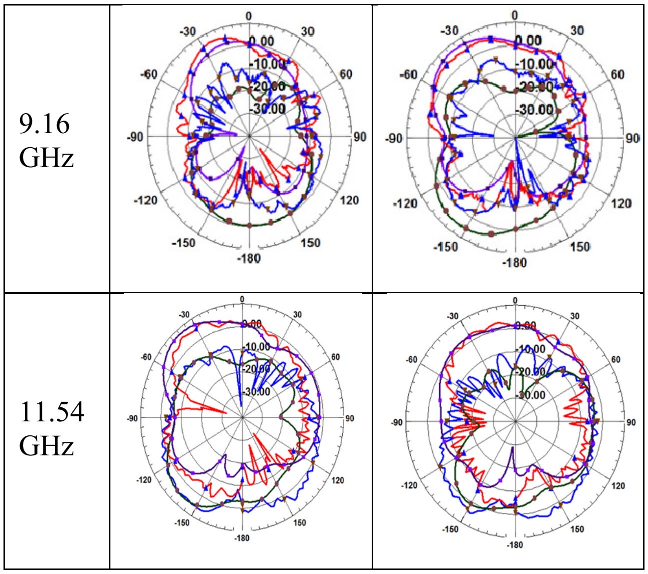


Fig. 11. Simulated and measured LHCP and RHCP radiation patterns for the Mod Arspl fabricated on the microwave substrate at different frequencies.

ACKNOWLEDGMENT

This work was carried out under the National Science Foundation (NSF)'s CAREER grant # ECCS-0845822.

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Satish Kumar Sharma received his Ph. D. degree from the Institute of Technology, Banaras Hindu University, in 1997 in Electronics Engineering. From December 1993 to February 1999, he was a Research Scholar in the Department of Electronics Engineering, Institute of Technology, Banaras Hindu University. From March 1999 to April 2001, he was a Postdoctoral Fellow in the Department of Electrical and Computer Engineering, University of Manitoba. He was a Senior Antenna Engineer with InfoMagnetics Technologies Corporation in Winnipeg, Canada, from May 2001 to August 2006. Simultaneously, he was also a Research Associate at the University of Manitoba from June 2001 to August 2006. In August 2006, he joined San Diego State University (SDSU) as an Assistant Professor in the Department of Electrical and Computer Engineering. Since August 2010, he is an Associate Professor at SDSU. Dr. Sharma received the National Science Foundation's prestigious faculty early development (CAREER) award in 2009. Currently, he serves as an Associate Editor of the IEEE Transaction on Antennas and Propagation journal. He is a full member of the USNC/URSI, Commission B, Senior Member of the IEEE (Antennas and Propagation Society) and a Member of ACES since year 2010.