IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 5, 2019, accepted December 24, 2019, date of publication January 6, 2020, date of current version January 14, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2964008

Circularly-Polarized Shaped Pattern Planar Antenna for Aerial Platforms

HAMZA NAWAZ[1], **XIANLING LIANG**[1], **(Senior Member, IEEE),**
MUHAMMAD SHAHZAD SADIQ[2],
JUNPING GENG[1], **(Senior Member, IEEE),**
AND RONGHONG JIN[1], **(Fellow, IEEE)**
[1]Department of Electronics Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[2]School of Information and Electronics Engineering, Beihang University, Beijing 100083, China

Corresponding author: Hamza Nawaz (hamza_nawaz@hotmail.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61571298, Grant 61671416, and Grant 61471240, and in part by the Natural Science Foundation of Shanghai under Grant 17ZR1414300.

ABSTRACT Circularly-polarized planar antenna with a shaped pattern for airborne applications, is proposed in this letter. The proposed antenna consists of vertically-polarized formation and horizontally-polarized stubs to provide circularly-polarized configuration, which is loaded by a copper curl based top layer to control current distribution for beam shaping and filling of zenith null. The antenna also contains split ring resonators beside partial ground to make it deployable over larger ground planes (metallic bodies) without distorting circular polarization by controlling phase of reflected waves. The power density of presented airborne shaped pattern antenna differs for variant elevation and azimuth angles, to have uniform wireless coverage over the earth's surface by managing variations of the signal strength because of different path lengths. The demonstrated antenna also possesses circular polarization and direction based circular polarization diversity at angles against the greatest path-lengths. Antenna retains a null-filled pattern in the vertical plane along with having high absolute peak gain (5.5 $\pm$ 1 dBi) and adequate peak polarization gain (2 to 4 dBi) through-out the operational bandwidth from 2.82 GHz to 2.89 GHz (Measured reflection coefficient less than -10 dB). Moreover, the radiating element exhibits omnidirectional radiation characteristics, with good horizontal gain (greater than -3.6 dBi).

INDEX TERMS Pattern-shaping, circular polarization, null-filled radiation, airborne antenna.

I. INTRODUCTION

Antennas are always regarded as an essential part of wireless systems, whereas their radiation and polarization characteristics play a vital role in defining the performance and efficiency of such systems [1], [2]. Thus, the focus is on the radiation-pattern shaping of the antenna as per application requirements, using various techniques, generally using multiple radiating elements, embedded coding, or bulky structures [3]–[6]. Applications for which antenna is to illuminate various angles at different path lengths; it is worthy of achieving radiation configuration of arbitrary, application-oriented shape and fixed response ripple [7]–[9].

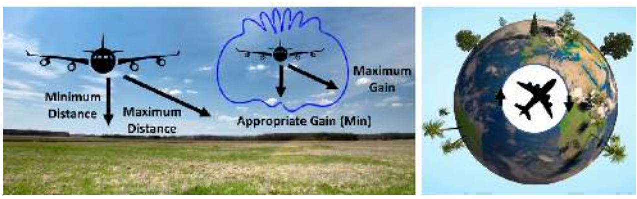
On the other hand, circular polarization and circular polarization diversity are in demand to provide additional value to the performance of communication systems. Circularly-polarized antennas have valuable properties like suppression of multipath interferences, combating Faraday rotation effect of the ionosphere, and provision of flexible orientation/alignment between transmitter and receiver by minimizing polarization mismatch losses, which are quite worthy characteristics for modern wireless applications [10], [11]. Besides that, circularly-polarized waves possess benefits of weather penetration and better mobility [12]. Antenna diversity techniques are generally used to increase the data capacity of wireless systems [13]–[15]. Direction based circular polarization diverse antenna in combination with mechanical rotator or digital control can be beneficial to receive two orthogonally polarized signals from different directions without crossover, using a single antenna, which leads to an increase in traffic handling capacity. Moreover, such blends can help to avoid signal fade, form polarization-based

The associate editor coordinating the review of this manuscript and approving it for publication was Yasar Amin.

sectors, and to provide better functional efficiency for airborne microwave systems.

At airborne applications, linearly polarized protruding antennas like that of blade or stub antennas are generally installed [16], [17]. Apart from losing circular polarization benefits, such antennas lead to an increase in radar cross-section (RCS), cause considerable drag and wind noise, are considered structurally weak, and are more susceptible to corrosion and damage due to the air-stream or high aero heating atmospheric conditions [18]–[21].

Desirable radiation beam shape for the airborne antenna is meant to provide smooth/unhindered communication in all hemispherical directions (at both elevation and azimuth plane), by having different gain amplitudes at variant angles to cover various distance ranges, as shown in Figure 1. An airborne antenna needs to have peak gain at pitch angles where the aerial vehicle is to grab maximum range, along with the availability of a reasonable amount of gain in all hemispherical directions for the unimpaired realization of wireless access. However, at airborne applications, very long-distance communication is generally not being conducted at acute elevation angles due to vegetation, uneven train, and earth's curvature, so the signal strength required at such angles is less as compared to the gain against most distant points [8], [22]. Antenna for aerial platform requires to attain omnidirectional radiation pattern in a horizontal plane to ensure signal coverage in all yaw directions [23].



(a) (b)

FIGURE 1. Desired beam pattern for aerial platforms. (a) Elevation (Pitch); (b) Azimuth (Yaw).

In the recent past few papers have been published proposing planar and conformal antennas targeting airborne applications [8], [22], [24], [25], mainly to provide an alternative for catering issues caused by protruding elements. Nevertheless, all of these papers demonstrated linearly polarized antennas. The antenna configuration proposed in this paper is one of its kind, which along with targeting pattern shaping, provides circular polarization at angles where the target is to achieve maximum range. Circular polarization providing a gain advantage against the greatest path lengths is very worthy for long-distance communication. Apart from targeting the benefit of covering more illumination range, the proposed antenna also provides direction based polarization diversity. Such antennas can be worthy of modern aerial platforms for data sectoring and secure communication, apart from grabbing other benefits of polarization diversity. Another issue catered during the design is the compatibility of circularly polarized configuration over the metallic airborne structure. Circular polarization gets affected due to the reflections from a metallic structure. In 2015, a circularly polarized conical beam antenna was proposed having the capability to be mounted over large ground planes [26]; however, antenna have a deep null and is not designed for airborne surface mount applications. The designed configuration presented in this paper proposed the use of split-ring resonators to avoid circular polarization distortion and provide mounting compatibility with metallic vehicular structures. The use of absorbing paints and scattering sheets is another method to avoid circular polarization distortion, but such arrangements reduce the efficiency of the overall antenna. By using split-ring resonators, along with avoiding circular polarization distortion, the energy of reflected waves can be utilized to achieve better total efficiency.

In this letter, a planar, conformal antenna having an omnidirectional azimuth pattern, stable horizontal gain, and null-filled radiation characteristics in the elevation plane is proposed, which fulfills beam shape requirements of airborne applications. On top of that, the presented antenna also possesses direction based circular polarization diversity (left-hand circular polarization and right-hand circular polarization) and circular polarization gain against pitch angles that are intended to have maximum gain amplitude, to further increase communication range against most distant points. The proposed antenna also possesses split-ring resonator structures for having the capability to be mounted over the metallic vehicular body without circular polarization distortion. The letter is arranged as follows. The geometry and design methodology of the proposed antenna is elaborated in Section II. Section III contains an analysis of simulated and measured results, whereas section IV is the conclusion.

II. ANTENNA DESIGN AND GEOMETRY

The proposed circularly-polarized pattern shaped antenna illustrated in Figure 2, comprises of a single-fed structure implemented using Roger RT/duroid 5870 ($\varepsilon r = 2.33$), having radius of 62mm. Its construction consists of three layers, demonstrated in Figure 3, while developed prototype of each layer is visible in Figure 4. Middle layer is setting up a circularly-polarized radiator, top layer is to achieve null-filled pattern characteristics, whereas bottom layer provides

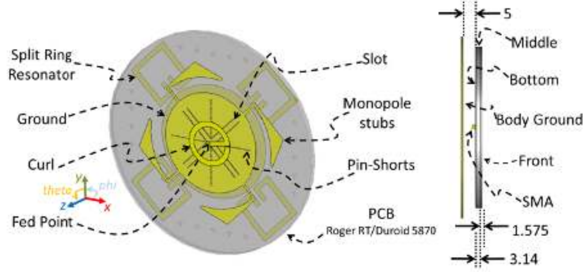


FIGURE 2. Proposed circularly-polarized shaped pattern antenna structure.

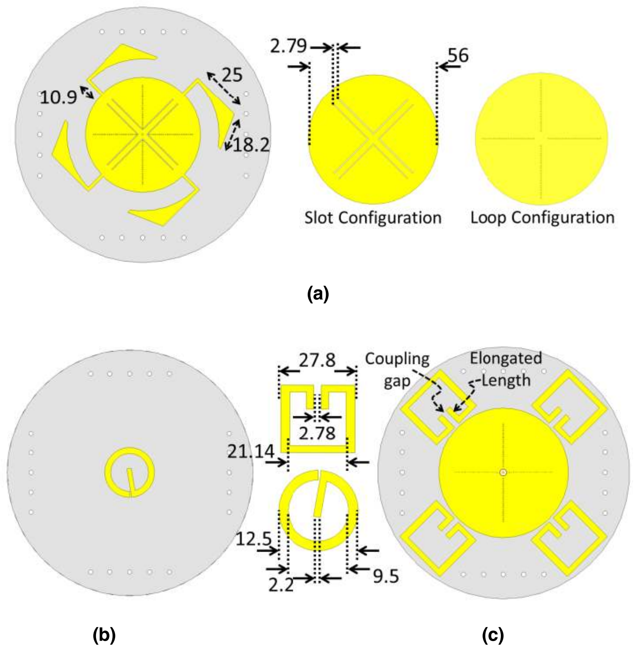


FIGURE 3. Layout of antenna with dimensions in millimeters (a) Middle Layer (b) Top Layer (c) Bottom Layer.

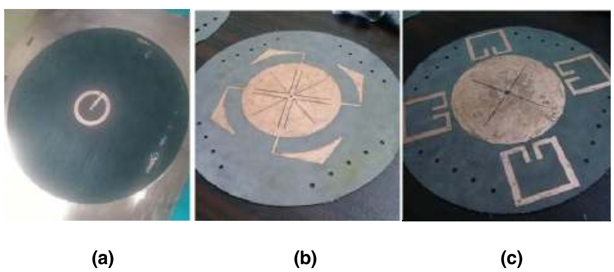


FIGURE 4. Fabricated prototype (a) Top layer (b) Middle layer (c) Bottom layer.

ground and control phase of reflected waves to avoid circular polarization distortion when being mounted over metallic surface.

The middle layer is composed of vertically-polarized slot-loop formation and horizontally-polarized stubs to create the circularly-polarized omnidirectional pattern. The radius of the circle-shaped patch over which slot-loop configuration is embedded defines the operational frequency of the antenna. Length and width of engraved slots are set to realize λ/4 transformers with an impedance of 200Ω each; so that perfect 50Ω impedance matching can be achieved at the center of the patch (fed-point) [8], whereas ground shortening pins are utilized for loop realization. The center-fed symmetric structure provides the benefit of having radiation pattern symmetry along the horizontal plane. Sometimes hybrid-fed configurations are designed to attain circular polarization; such antennas may cause power losses and efficiency decline because of input source split. Moreover, it is more difficult to obtain radiation pattern symmetry along azimuth plane in-case of dual-fed or multi-fed antennas in comparison to that of center-fed antennas [27]. Four feed branches are extended from patch to stimulate horizontally-polarized monopole stubs. The length of curved monopole stubs is optimized to grab desired functional frequency in-correlation to that of the working frequency of the vertically polarized radiator, while gradually narrow outer curved stubs provide better circularly-polarized fields by giving improved phase matching of electric vectors [28].

An asymmetric layer is placed over a circularly-polarized formulation to compensate its pitch null and make antenna prospective candidate for aerial systems by beam-shaping and null-filling. The top layer contains a copper curl, excited from the same point to that of the middle layer resonator, to enhance current concentration towards the center, hence emitting flux and altering radiation pattern shape. Top layer curl is stimulated using uni-directional feeding branch, because of which the direction of current flow at the point of contact (between copper curl and feeding branch) is reversed to that of current's direction at the opposite end of the curl. Generation of dominant propagating field components in opposite directions (to that of each-other) at two halves of antenna, assists in creating direction based circular polarization diversity; left-hand circular polarization and right-hand circular polarization at mirror directions of elevation pattern. Outer-radius/inner-radius ratio of the circular curl outlines the directivity of the generated beam-pattern; more the ratio greater will be the directivity [29]. When the curl width reaches half the value of the wavelength of the antenna (wavelength of the center frequency in free space), higher-order TM modes appear. To generate inner and outer fringing fields of the same polarity, single order mode has been generated (curl width (.03cm) < half value of λ (.104/2 =.05). Hence, the thickness of the curl is selected as 3mm to achieve good null-fill characteristics along with maintaining single-mode operation.

Meanwhile, the below-mentioned equation is used to design curl against desired frequency

$$\textit{Resonant Frequency} = (\chi_{12}\, c)/(2\pi a\sqrt{\varepsilon_r})$$

where 'c' is the speed of light, 'a' represents the inner radius of the curl, and 'εr' denotes relative permittivity.

A well-known characteristics equation [30]

$$J_n'(kb)Y_n'(ka) - J_n'(ka)Y_n'(kb) = 0$$

has been used to find roots and calculate value of $\chi 12 = 4.34$; where b/a = Outer radius / Inner radius = 6.25 / 4.75 = 1.31 mm, k is the propagation constant, and Bessel functions of first and second kind are denoted by Jn(x) and Yn(x), respectively.

Thickness of the curl is carefully set to fill the zenith null and to create the desired radiation shape; by grabbing appropriate amount of current at the center and at the same time by not grasping too much current that may cause beam pattern distortion, by shifting peak gain towards the angle perpendicular to that of aerial vehicle or by affecting horizontal gain.

Zenith null is to be filled (more than −10 dB) to avoid blanking of airborne systems at perpendicular angles [22], [31]; while maintaining an adequate amount of horizontal gain to refrain dropping of communication range at acute angles.

The bottom layer is carved at the opposite side to that of the middle layer, over a double-sided PCB (Printed circuit board). Parameters of circularly-polarized antennas generally get affected while being mounted over vehicular platforms because of intense field coupling between metallic structures (body ground) and antenna [28]. To cater to radiation efficiency distortion at the operating frequency and to avoid circular polarization degradation, split ring based structures are used, along with partial ground at the bottom layer. Spacers are positioned underneath the bottom-layer to maintain a gap between designed antenna structure and body ground. The split-ring configuration unit cell comprises a squared split ring resonator with a coupling gap and elongated length between the two symmetrical parts of the structure [32]. The partial ground plane covers the area beneath the vertically-polarized patch, while split ring structures are placed under horizontally-polarized monopole stubs. The shape of the split-ring resonator cell and the air-gap between split-ring arrangement layer and body ground defines the built-in anisotropic behavior and LC resonance, which provides control over phase of reflected electromagnetic wave [32], [33]. The distance between split-ring resonators and the body ground is adjusted and optimized, to manage phase harmony between radiated wave and reflected wave to prevent circular polarization distortion and to acquire high gain. Moreover, freedom of getting mounted over larger metallic surfaces because of phase control characteristics of split-ring resonator structures helps the proposed antenna to have minimized the back-lobe level and better beam-shaping.

III. SIMULATED AND MEASURED RESULTS

The proposed planar antenna is designed for surface mount application (to be mounted over aerial platform). Mountable antenna characteristics mainly polarization and radiation pattern are a function of the aerial platform, as these parameters get affected due to the reflections from an aerial vehicle body [28]. To analyze those effects and workability of the proposed antenna under reflections, a metallic plate has been used beneath the proposed antenna configuration, visible in Figure 2 (labeled as body ground). Simulated and measured results of the proposed antenna are taken using a smooth circle-shaped copper plate of radius 140 mm.

S-parameter simulation has been carried out using CST (Computer Simulation Technology) simulator, and the measured result of the fabricated prototype was extracted using Agilent Vector Analyzer. Simulated and measured reflection-coefficient contours of the proposed antenna are illustrated in Figure 5. The measured result depicts that the designed radiating element is effectively operational over the frequency band of 2.82 GHz to 2.89 GHz. Simulated and Measured results are well in harmony, offering impedance bandwidth of 70 MHz.

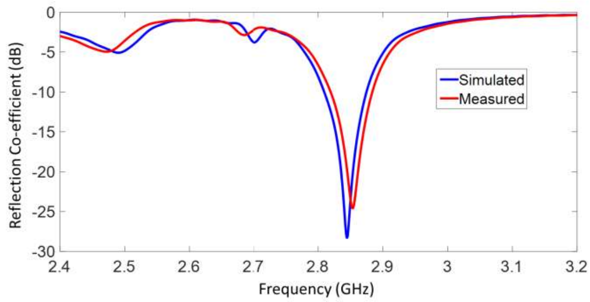


FIGURE 5. Simulated and measured reflection co-efficient of proposed antenna.

Figure 6 displays the simulated and measured radiation patterns of the proposed antenna. Radiation characteristics are measured along xz-plane (vertical plane), xy-plane (horizontal plane), and beside 60° elevation angle plane (theta = 60°) at two different frequencies that are 2.84 GHz and 2.87 GHz.

Beam contour at pitch-plane shows the null-filled shaped pattern, having the minimum but adequate amount of perpendicular gain (more than −6 dB), along with achieving circular polarization gain and direction based circular polarization diversity against angles with maximum signal strength (60° elevation angle plane). Measured circularly-polarized beam-width in xz-plane is 23° (left-hand circular polarization) against phi 20° to 188° and 22° (right-hand circular polarization) against phi 196° to 10° at 2.84 GHz and 22° (left hand circular polarization) against phi 21° to 189° and 24° (right hand circular polarization) against phi 198° to 9° at 2.87 GHz. Gain roll-off of the radiation beam at pitch-plane is smooth and slow, pattern contour tends to move from the minimum (at perpendicular (0°)) to the maximum amplitude (60° from the perpendicular) and then from the maximum to relatively lower gain (at small pitch angles); while sustaining good and appropriate gain in all hemispheric directions. Gain magnitude distribution at the vertical plane indicates that the main-lobe carries the major part of flux concentration whereas the back-lobe is limited.

Azimuth-plane of antenna exhibits omnidirectional radiation characteristics, worthy of providing coverage at all yaw angles. The proposed antenna possesses good horizontal gain, comparable with a gain of the simple monopole antenna. Figure 6 also flaunts that the radiation characteristics of the antenna remain stable and similar through-out the operational frequency band.

The simulated and measured axial ratios are shown in Figure 7, which are very well in harmony. Results present that both the 3 dB LHCP and RHCP axial ratio bandwidths are achieved against the entire 10 dB impedance bandwidth of 70 MHz, covering different directions, hence providing direction based circular polarization diversity. Simulated peak RHCP gains vary from 2 dBi to 4 dBi, whereas simulated peak LHCP gains variate between 2 dBi to 3.4 dBi against the operational frequency band that is from 2.82 to 2.89 GHz.

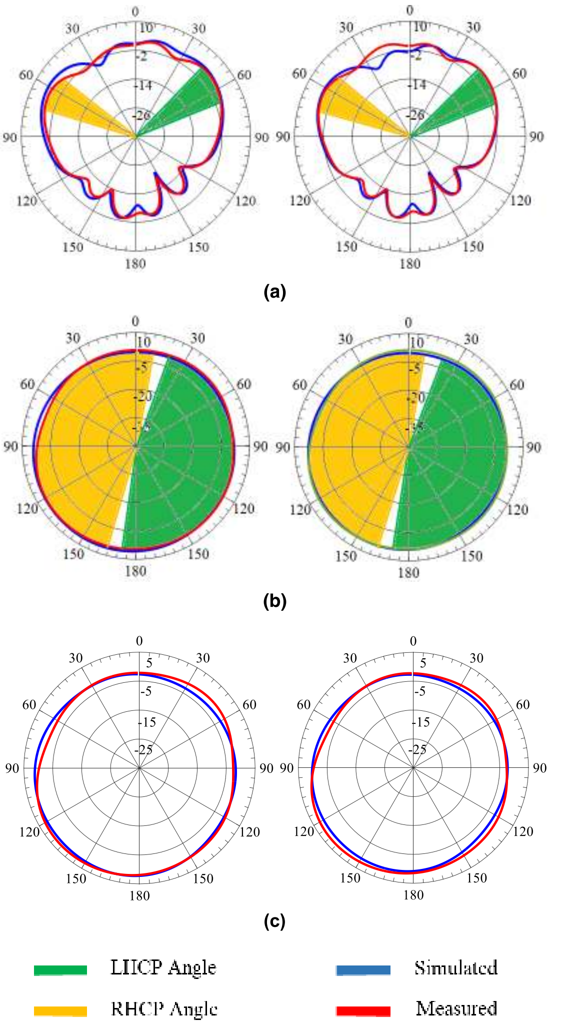


FIGURE 6. Radiation patterns of demonstrated antenna at 2.84 and 2.87 GHz respectively (a) xz-plane (b) 60° elevation angle plane (c) xy-plane Green color represents angles where antenna have LHCP Gold color represents angles where antenna have RHCP Blue contours represent simulated results Red contours represent measured results.

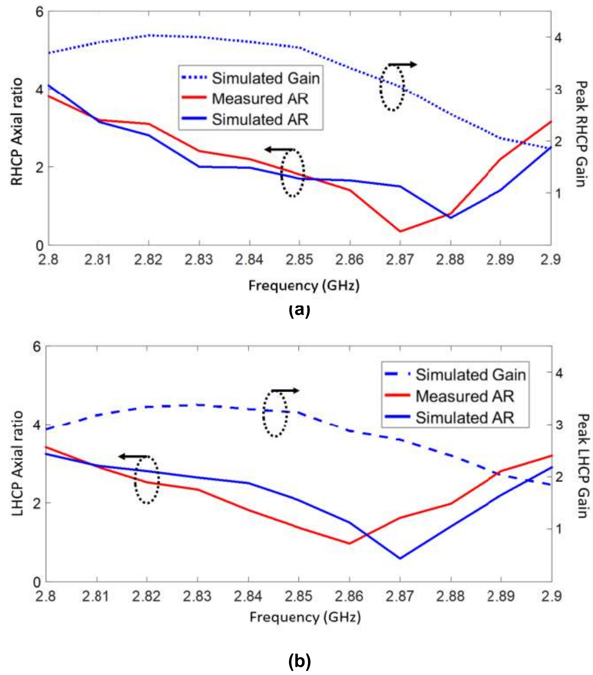


FIGURE 7. Axial ratio and circular polarization gain of proposed antenna (a) RHCP (b) LHCP.

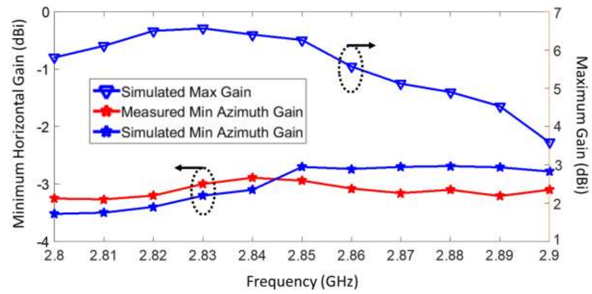


FIGURE 8. Minimum horizontal gain and peak gain of shaped pattern antenna.

Figure 8 depicts minimum horizontal gain and maximum 3D gain over the functional frequency band. Proposed null-filled beam shaped antenna retain good minimum horizontal gain (greater than -3.5 dBi) and high peak again (5.5 ± 1 dBi) against the whole operational frequency band. Thus, the proposed antenna exhibits very promising and worthy radiation characteristics at all pitch and yaw angles, making the antenna a really good option for aerial platforms.

Even though the proposed antenna is unique in the essence of providing pattern-shaping (with respect to that of aerial platform requirements), in combination with circular polarization and surface mounting compatibility; a comparison table is provided with the state of the art flush-mount/conformal designs published in recent years, targeting airborne applications.

Table 1 exhibit the parametric comparison of the proposed antenna configuration with other state of the art designs. Results show, that though polarization is the main advantage over all the other antenna designs, but it is not the only one, when it comes to achieving desired pattern for airborne applications. Results present, that antennas referred as [24] and [25] show uni-directional behavior, though they are designed for aerial platforms, but are not covering lower acute angles and have limited beam-width. All antennas other that of [8] have larger profile in comparison to that of the configuration proposed in this paper. Although [8] has size advantage over recently presented work, but it significantly lacks when it comes to zenith gain. Hence, comparison table flaunts that the proposed antenna configuration is superior candidate for long-range airborne communication systems.

IV. CONCLUSION

A circularly-polarized, pattern shaped antenna is proposed in this letter. Union of vertically-polarized slot-loop formation and horizontally-polarized monopole stubs have been used to realize circularly-polarized arrangement, which is further overlapped by an asymmetric curl to attain different

TABLE 1. Comparison with other antennas designed for aerial platforms.

Ref	Center Freq. (GHz)	Polarization	Height (Antenna Profile)	Zenith Gain (dB)	Min Azimuth Gain (dB)
[8]	2.6	Linear	.04 λ	-9.5	-2.85
[22]	6	Linear	.14 λ	-1.3	-4.5
[24]	2.1	Dual (Linear)	.26 λ	8	< -10 (Dir.)
[25]	2.4	Linear	.13 λ	4.5	< -10 (Dir.)
This work	2.85	Circular	.09 λ	-3	-3.5

radiating energy concentrations at different angular directions and to achieve circular polarization diversity at angles against most-distant points. Moreover, demonstrated antenna got split-ring resonator structures at the bottom layer to make it mountable over metallic vehicular bodies without distorting circular polarization. Proposed antenna possesses different gain amplitudes at various hemispherical angles (to cater beam shaping requirements of airborne application), slow signal-strength roll-offs in the elevation plane, omni-directional azimuth plane, appropriate horizontal gain, good polarization gains and stable radiation characteristics all over the functional frequency band. The designed antenna also offers benefits of being planar, conformal, and surface mount to make it suitable for the aero-dynamic environment and not to have extravagant RCS.

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HAMZA NAWAZ received the B.S. degree in electrical (telecommunication) engineering from the COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2011. He is currently pursuing the M.S. degree in electronics science and technology (focused on electromagnetics) with the Modern Antenna Research Center, Shanghai Jiao Tong University, Shanghai, China.

From 2011 to 2012, he worked as a RF Design Engineer. From 2012 to 2017, he was an Assistant Manager Telecommunication with Advanced Engineering Research Organization, Pakistan. He has authored or coauthored 20 publications in peer-reviewed International journals and conferences. His research interest includes RF and microwave circuits, dielectric resonator antennas, beam-shaped antennas, and partial reflecting surfaces.

XIANLING LIANG (Senior Member, IEEE) received the B.S. degree in electronic engineering from Xidian University, Xi'an, China, in 2002, and the Ph.D. degree in electric engineering from Shanghai University, Shanghai, China, in 2007.

From 2007 to 2008, he was a Postdoctoral Research Fellow with the Institut National de la Recherche Scientfique, University of Quebec, Montreal, QC, Canada. In 2008, he joined the Department of Electronic Engineering, Shanghai Jiao Tong University (SJTU), Shanghai, as a Lecturer, and then became an Associate Professor, in 2012. He has authored or coauthored over 250 articles including 141 journal articles and 113 conference papers, and coauthored one book and three chapters, in microwave and antenna fields. He holds 15 patents in antenna and wireless technologies. His current research interests include OAM-EM wave propagation and antenna design, time-modulated /4-D array and applications, anti-interference antenna and array, integrated active antenna and array, and ultrawideband wide-angle scanning phased array.

Dr. Liang was a recipient of the Award of Shanghai Municipal Excellent Doctoral Dissertation, in 2008, the Nomination of the National Excellent Doctoral Dissertation, in 2009, the Best Paper Award presented at the International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Materials, in 2010, the SMC Excellent Young Faculty and the Excellent Teacher Award from SJTU, in 2012, the Shanghai Natural Science Award, in 2013, the Best Paper Award presented at the IEEE International Symposium on Microwave, Antenna, Propagation, and EMC Technologies, in 2015, the 4th China Publishing Government Book Award, and Okawa Foundation Research Grant, in 2017.

MUHAMMAD SHAHZAD SADIQ was born in Karachi, Pakistan, in 1983. He received the B.E. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, in 2005, and the M.S. degree in electrical engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in March 2012. In September 2018, he joined the School of Electronics and Information Engineering, Beihang University, Beijing, China, as a Ph.D. Scholar. His current interest includes airborne antennas and high gain omnidirectional antennas.

JUNPING GENG (Senior Member, IEEE) received the B.S. degree in plastic working of metals, the M.S. degree in corrosion and protection of equipment, and the Ph.D. degree in circuit and system from the Northwestern Polytechnic University, Xi'an, China, in 1996, 1999, and 2003, respectively.

From 2003 to 2005, he was a Postdoctoral Researcher with Shanghai Jiao Tong University. In April 2005, he joined as a Faculty Member with the Electronic Engineering Department, Shanghai Jiao Tong University, where he is currently an Associate Professor. From 2010 to 2011, he was a Visiting Scholar with the Institute of Electrical and Computer Engineering, The University of Arizona, Tucson, AZ, USA. He has authored or coauthored over 300 refereed journal articles and conference papers, three book chapters, and one book. He holds over 60 patents with over 40 pending. He has been involved with multiantennas for terminals, smart antennas, and nano-antennas. His main research interests include antennas, electromagnetic theory, and computational techniques of electromagnetic and nano-antennas.

Dr. Geng is a member of the Chinese Institute of Electronics (CIE). He was a recipient of the Technology Innovation Award from the Chinese Ministry of Education, in 2007 and the Chinese Government, in 2008.

RONGHONG JIN (Fellow, IEEE) received the B.S. degree in electronic engineering, the M.S. degree in electromagnetic and microwave technology, and the Ph.D. degree in communication and electronic systems from Shanghai Jiao Tong University (SJTU), Shanghai, China, in 1983, 1986, and 1993, respectively.

In 1986, he joined the Department of Electronic Engineering, SJTU, where he was an Assistant, a Lecturer, and an Associate Professor, and he is currently a Professor. From 1997 to 1999, he was a Visiting Scholar with the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Meguro, Japan. From 2001 to 2002, he was a Special Invited Research Fellow with the Communication Research Laboratory, Tokyo, Japan. From 2006 to 2009, he was a Guest Professor with the University of Wollongong, Wollongong, NSW, Australia. He is also a Distinguish Guest Scientist with the Commonwealth Scientific and Industrial Research Organization, Sydney, NSW, Australia. He has authored and coauthored over 400 articles in refereed journals and conference papers proceedings, and coauthored seven books. He holds more than 70 patents in antenna and wireless technologies. His current research interests include antennas, electromagnetic theory, numerical techniques of solving field problems, and wireless communications.

Dr. Jin is a Committee Member of the Antenna Branch, Chinese Institute of Electronics, Beijing, China. He was a recipient of the National Technology Innovation Award, the National Nature Science Award, the 2012 Nomination of National Excellent Doctoral Dissertation (Supervisor), the 2017 Excellent Doctoral Dissertation (Supervisor) of China Institute of Communications, the Shanghai Nature Science Award, and the Shanghai Science and Technology Progress Award.