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Compact Multi-Mode Quadrifilar Helical Antenna for GNSS-R Applications

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Abstract—In this paper, a compact circularly polarized (CP) multi-mode antenna for global navigation satellite system reflectometry (GNSS-R) is presented. The design comprises two Quadrifilar Helical Antennas (QHAs), each fed with a ground coplanar waveguide (GCPW) and quarter wavelength power divider (QWPD) integrated feed. A hybrid staircase-shaped (SSR) QHA radial is proposed, and it is formed by serially arranging several vertical and diagonal elements. The electric field lines from the vertical elements converge constructively to radiate with the axis normal. Besides, the circular spatial offsets between the adjacent diagonal and vertical elements induce a 90° delay in the field radiated. This hybrid shape launches an unprecedented theory facilitating normal mode of operation (MOOp) in QHA and generates CP over broad elevations and azimuths ($0^\circ < \theta < 80^\circ$ and $0^\circ < \phi < 360^\circ$). Besides, the port-to-port 90° spatial offset and the GCPW architecture yield high isolation ($>20\text{dB}$). Unlike conventional GNSS-R antennas, this compact ($170.5\text{ mm} \times 132\text{ mm}$) configuration operates in axial and normal mode, offers a broad beam coverage (237°), minimizes pattern interference between the two QHAs upon gap-free stacking, and ensures high delay accuracy in the remote sensing data computed. Additionally, it supports proficient (efficiency >0.9) multi-constellation remote sensing. The design prototype was fabricated and measured, and the measurements agreed well with the simulations.

Index Terms—Circular polarization, Global Navigation Satellite System Reflectometry (GNSS-R), Quadrifilar Helical Antenna (QHA)

I. INTRODUCTION

GLOBAL Navigation Satellite Systems-Reflectometry (GNSS-R) is a real-time Microwave Remote Sensing (MRS) technique [1] - [2]. It has received much attention in recent years due to its capability to address wide-ranging applications and produce information with a high spatial resolution [1], [3]- [4]. The GNSS-R system consists of two antennas (conjointly addressed as GNSS-RAP), two recorders, and a processing software [5]. According to its operation principle, the correlation between received direct (D-GNSS) and ground-reflected GNSS (R-GNSS) signals are exploited to infer the physical composition of the reflected surface [6]. But, the D-GNSS signal is polarization flipped (right-hand circular polarization (RHCP) to left-hand CP (LHCP)) upon reflection

[2]. Conventionally, a GNSS-RAP comprises CP L-Band (1-2 GHz) operated antennas [7]. Nonetheless, a compact GNSS-RAP aids portability and a tight emplacement of its antennas ensure high delay accuracy in the sensed data [8].

Previously, the number of GNSS-R Antennas developed is limited, so few GNSS antennas reported will be reviewed for their compatibility of integration into the GNSS-R system [5], [9]- [12]. A tapered helix antenna in [5] and a 5-turn bifilar helix antenna in [9] had massive structures and limited the system mobility upon integration. An annular ring microstrip antenna in [10] is fed with a microstrip (MS) feed line and is vulnerable to pattern interference and degradation upon tight emplacement into the GNSS-R system. A printed linearly polarized Yagi-Uda GNSS antenna in [11] suffers a high polarization loss factor due to misalignment between the incoming and designated radiation polarization, and if integrated, will make the system unreliable for real-time operations. In [12], a reduced-surface-wave GNSS antenna fed by proximity coupled probe (PCP) exhibits a narrow half power beamwidth (HPBW) and reduces its potential to capture from the GNSS satellites.

In this paper, we propose a GNSS-RAP. The configuration consists of two Quadrifilar Helical Antennas (QHAs), each fed with ground coplanar waveguide (GCPW) - Quarter Wavelength Power Divider (QWPD) integrated feed. The feeding networks of QHAs are aligned perpendicular to each other, launching orthogonal field vectors. The GCPW configuration latches the traveling electric-field (E-field) lines between its ground plates and prevents field leakage between the QHAs. The GCPW and the 90° spatial port offset in the proposed design support mutual coupling reduction and enable the gap-free construction of two QHAs. Besides, this GNSS-RAP operates in dual mode (axial and normal). The strategically assembled and spaced (equidistant from its adjacent self) elements in the hybrid Staircase Shaped Radials (SSR) shown in Fig. 1 helps obtain a normal mode of operation (MOOp) with low elevated CP (on the transversal plane at $0^\circ < \theta < 80^\circ$). The delay lines in QWPD induce a 90° phase offset in power fed to the QHA radials, and the folding of QWPD delay lines aid miniaturization. Ultimately, as a GNSS-RAP, the antenna is a sound candidate for this application due to its dual MOOp, compact size, and gap-free configuration.

II. ANTENNA DESIGN AND CONFIGURATION

A. Antenna Design

Fig. 1 depicts the proposed GNSS-RAP configuration. The structure (exploded view presented in Fig. 1 (a)) consists of

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Fig. 1. The proposed GNSS-RAP configuration (a) Composition (b) Feed Geometry (c) Perspective view (d) Farfield plot coordinates (e) Simulated phase shift between delay lines at GPS L1 (1.575 GHz). $|S_{21}|$ represents 0° , $|S_{51}|$ represents 90° , $|S_{41}|$ represents 180° and $|S_{31}|$ represents 270° .

two QHAs (QH_{ax} and QH_n), each fed by a GCPW-QWPD feed. QH_{ax} operates in axial mode to capture D-GNSS and QH_n in normal mode to captures R-GNSS. Conventional helix radiates along its axis when its circumference (C) is around one wavelength [13], so the QHA's C is chosen to be 0.94 wavelengths (180 mm). Each QHA accommodates four radials (SSR and Diagonal Shaped Radial (DSR)), equidistant from one another placed circularly over its corresponding feed. The SSR (in QH_n) composes segments of length l_{n1} and l_{n2} , and DSR in QH_{ax} is of length, L_{ra} . The DSR enables QH_{ax} to radiate CP signals along the axis (axial-mode). Whereas, SSR made two mighty contributions: First, by the reconstruction of the top view circular geometry of non-fed radials on the side of the structure with the combination of vertical and diagonal elements (l_{n2} and l_{n1}), the trace of a circular electric field is induced with a relative phase-shifted signal on the axis normal; second, by the sum of electric fields radiated by the short vertical elements (l_{n2}), normal-mode radiation is produced. These $SSRs$ and $DSRs$ are excited by the feed.

Fig. 1 (b) outlines the feed network. The GCPW feed structure comprises a dielectric substrate (Rogers RT5880 with $\epsilon_r = 2.2$ and thickness= 0.787 mm) sandwiched by three metal (copper) ground plates. The QWPD with delay lines is embedded on the underlying dielectric substrate. The QWPD equally divides the power with lines of widths, w_{70} (70 Ω) and w_{50} (50 Ω). The delay lines (namely, la_0 , la_{90} , la_{180} , la_{270} , ln_0 , ln_{90} , ln_{180} , ln_{270}) induce a 90° phase delay in the power fed to the radials and the delay pattern (progressive/regressive)

TABLE I
GEOMETRICAL PARAMETERS

H_a	62.7	l_{50c}	3	ln_{03}	11.02	la_{2702}	18.64
H_n	106.2	l_{70}	18	ln_{04}	30.87	la_{2703}	18.29
H_f	0.789	w_{70}	1.45	l_{90}	40	la_{2704}	19.42
D_a	57.3	w_{50}	2.53	l_{901}	1.71	la_{2705}	13.89
D_f	132	gap	2	la_{902}	31.1	la_{2706}	7.96
w	5	l_0	74	la_{903}	2.1	la_{2707}	4.25
L_{ra}	140.25	la_{01}	5.95	l_{904}	5	l_{2708}	5
$\angle l_n, \angle l_r$	115	la_{02}	26.96	ln_{902}	30.1	ln_{2701}	8
l_{n1}	14.75	la_{03}	9.91	ln_{903}	3.06	ln_{2702}	10.78
l_{n2}	10.7	la_{04}	31.18	l_{180}	10.8	ln_{2703}	14.06
l_{50}	20	ln_{01}	5.75	l_{270}	99	ln_{2704}	44.41
l_{50a}	8	ln_{02}	26.35	la_{2701}	11.50	ln_{2705}	16.81

*All measurements specified are in mm

defines the radiation mode (end-fire / back-fire mode). Unlike, the conventional microstrip line feed, the diverging E-field on the feed line is sandwiched by the GCPW's ground plates, latching them in the feed, preventing E-field leakage from one QHA to the other, and decreasing the mutual coupling between the QHA's. Besides, as observed from Fig. 1 (c), the ports aligned perpendicular to each other provide orthogonality in the field vector, isolating the two ports and reducing the mutual coupling even further. Table I presents the geometrical parameters of the configuration.

B. Parametric study

This subsection identifies the key factors affecting GNSS-RAP radiation performance and provides design guidelines.

Fig. 2. Parametric analysis, effect of (a) D_a (mm) on RP (b) w_a (mm) and w_n (mm) on $|S_{11}|$ (c) L_{ra} (mm) on $|S_{11}|$ (d) $\angle L_n$ on RP (e) $\angle L_r$ on RP (f) l_{n1} (mm) on RP (g) l_{n1} (mm) on $|S_{11}|$

The study in Fig. 2 (a)-(g) corresponds to QHA without GCPW-QWPD feed. Fig. 2 (a) shows that the change of D_a has no influence on the QHA's MOOp and that its radiation remains intact. Fig. 2 (b) indicates that the impedance bandwidth widens, when (w_a / w_n) increases. Fig. 2 (c) signifies that the antenna center frequency shifts higher when constructed with a DSR lower than 150 mm. With Fig. 2 (d), it is observable that with the change of $\angle L_n$ from 115° to 180° , the main beam gradually alters from $\theta = 90^\circ$ to $\theta = 0^\circ$. The aforementioned shows the influence of the SSR's vertical element (l_{n2}) to excite normal MOOp in the QH_n . The QH_n can be made to resonate at a frequency higher by increasing l_{n1} from 8.8 mm to 17.2 mm, as demonstrated with Fig. 2 (g). It must be noted that the l_{n1} value in Fig. 2 (f) and (g) were altered, while the overall radial length of QH_n and l_{n2} were kept unaltered. Thus, in conclusion, the study implied the following. The QHA's D_a has no effect on its MOOp and HPBW, while the SSR's $\angle L_n$ plays an intricate role in altering its MOOp and HPBW. The QH_n structure can be constructed for other applications with the following guidelines. The frequency of operation of both antenna's can be altered by tuning the radial width (w_a / w_n) or radial overall length (L_{ra}). Alternatively, l_{n1} contributes in the structure's operating frequency, which can be modified while maintaining L_{ra} . Additionally, the bandwidth can be widened by tuning w_a / w_n , whereas the L_{ra} / l_{n1} is chosen corresponding to the band of interest. With the variation in $\angle L_n$. A variety of RP can be realized by tuning $\angle L_r$, $\angle L_n$,

Fig. 3. Elaborated Axial Ratio Calculation

Fig. 4. Axial Ratio Plot (a), and (b) for QH_{ax} . (c), and (d) for QH_n .

and l_{n1} according to Fig. 2 (d), (e), and (f). For instance, the HPBW and the MOOp of the antenna can be set differently by rotating the $\angle L_n$ while maintaining the operating frequency.

III. RESULTS AND DISCUSSION

In order to simulate the designed structure, the full-wave package CST Microwave Studio is used in this paper. To ease out AR calculation for this asymmetric structure, the AR calculation is done by employing perpendicularly aligned E-field probes (see Fig. 3 (a)) around the structure (see Fig. 3 (b)). The probe values (obtained from Fig. 3 (c)) are used to calculate axial ratio (adopting to method in Fig. 3 (d)) in this work. Fig. 4 reports the measured and simulated AR plot, representing an AR bandwidth (ARBW) at broadside and off-broadside directions. The ARs are reported at $\theta = 0^\circ, 90^\circ, 180^\circ$, and 270° in frequency = 1.5 GHz, 1.55 GHz, 1.6 GHz, and 1.65 GHz. The simulation agrees well with the measurement. A CP is obtained over the elevations spanning $\pm 60^\circ$ (QH_{ax}) and $\pm 80^\circ$ (QH_n) and at azimuths traversing the entire perigon in both QHAs. This multi-directional CP offers flexibility in capturing angles.

The E-field distribution is displayed in Fig. 5. As observed in Fig. 5 (a), the field produced by QH_{ax} is maximum along its axis, while for QH_n , it is directed normal to the axis (in the

Fig. 5. E-Field distribution at GPS L1 (1.575 GHz) (a) Magnitude (b) E-field vector Plot on SP.

Fig. 6. Fabrication Process (a) DSRs (in top) and SSRs (in bottom) (b) QH_{ax} feed. (c) QH_n feed. (d) QH_{ax} (e) QH_n (f) GNSS-RAP.

transverse plane) and agrees well with analysis in Fig. 2 (d). A study on the QH_n 's polarization is conducted by introducing vacuum planes in a simulation environment. The plots of the E-field vector (see Fig. 5 (b)) present the direction of vector rotation at four phases. The vector rotates as the phase varies from 0° to 270° . This rotation reported proves that the top view circular geometry of QHA is being mimicked on the side with an SSR arrangement. This circular placement on the side aided in producing wide axial ratio beamwidth (3dB-BW).

Fig. 6 summarizes the fabrication process of the proposed GNSS-RAP, and the outline of the steps is as follows. Initially, the DSRs and SSRs (in Fig. 6 (a)) are soldered and joined to their respective feeds (in Fig. 6 (b) and (c)). Then, as disclosed in Fig. 6 (d) and (e), the radials are wrapped around the foam cylinder ($\epsilon_r \approx 1$) and stabilized. Eventually, QH_{ax} and QH_n , with a 90° spatial offset maintained between ports, are fastened together with plastic bolts and nuts, as disclosed in Fig. 6 (f). The gap-free emplacement of QH_{ax} and QH_n ensures a higher delay accuracy in the GNSS-R data. The compact size ($170.5 \text{ mm} \times 132 \text{ mm}$) and the low profile grant unlimited mobility and eases its integration into automobiles, drones, etcetera.

The S-Parameters in Fig. 7 validates operation over the entire GNSS upper L-band. The measured bandwidth for QH_{ax} and QH_n is 1.5 GHz-1.8 GHz (300 MHz) and 1.44-1.8 GHz (360 MHz) with $|S_{22}|$ and $|S_{11}| < -10\text{dB}$. Lastly, mutual coupling ($|S_{21}|$ and $|S_{12}|$) between QH_{ax} and QH_n is $< -20\text{dB}$ across the operating band, implying its relative suppression.

The normalized radiation patterns are in Fig. 8. The far-field pattern displays a simulated HPBW of 105.5° and 237°

Fig. 7. Simulated and measured S-Parameter.

Fig. 8. Simulated and measured normalized radiation patterns (Co-Polar and Cross-Polar) at GPS L1 (1.575 GHz) of (a) QH_{ax} and (b) QH_n .

for QH_{ax} and QH_n . The measured cross-polarization rejection is -32 dB and -21 dB in QH_{ax} and QH_n over the HPBW. Besides, a measured front-back (F/B) radiation ratio of 10.1 dB (in QH_{ax}) and 12.2 dB (in QH_n) is recorded. The efficiency plot in Fig. 9 reports an in-band efficiency higher than 0.85 . The reported efficiencies are measured based on the *Directivity/Gain* method presented in [14]

Fig. 9. Simulated and measured efficiency of (a) QH_{ax} (b) QH_n .

The comparison of antenna metrics of QH_n with other QHA are shown in Table II. It compares the MOOp, HPBW, and 3dB-BW of various radial shapes with SSR. It is explicit that only QH_n works in normal mode but has relatively the same or lesser 3dB-BW than others. However, QH_n has the highest HPBW among QHA's in Table II.

TABLE II
PERFORMANCE SUMMARY

	MOOp	Frequency (GHz)**	HPBW	3dB-BW
[15]	Axial	GPS L1	180	150
[16]	Semi	GPS L1	210	160 (not <3dB over entire span)
[17]	Axial	0.137	120	NG*
[18]	Axial	0.95	103	<110
[19]	Axial	2	66	NG*
[20]	Isoflux	1.7	-	<140
[21]	Axial	1.54	180	160
[22]	Axial	GPS L1	74.8	Boresight
[23]	Axial	GPS L1	160	NG*
[24]	Axial	2.43	40	NG*
QH_n (This work)	Normal	GPS L1	237	160

* : Not given or the given was not computable in the reference papers.

** : The comparison is at GPS L1 or at comparable- if was reported. If RP at GPS L1 was not reported, the frequency that provided best RP is used.

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