Design of Low-Profile Dual-Band Printed Quadrifilar Helix Antenna With Wide Beamwidth for UAV GPS Applications

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ABSTRACT In the paper, a low-profile dual-band printed quadrifilar helix antenna (PQHA) with wide beamwidth is presented for UAV GPS applications. The antenna is composed of a hollow dielectric cylinder with four arms of dual-helix metal strips and a hollow dielectric ring with four pairs of circular metal strips. To provide dual-band operation, different lengths of the dual-helix metal strips are applied. By loading the circular metal strips on the dual-helix metal strips, size reduction of the antenna height is realized. Moreover, wide beamwidth is obtained. A miniaturized quad-feed network is also designed to provide equal amplitude signals with sequentially quadrature phases. To validate the proposed structure, a prototype is fabricated. The height of the antenna is 18.5 mm. The experimental results show that good impedance matching ($|S_{11}| < -18$ dB) and axial ratio ($< 2$ dB) are obtained at GPS L1/ L2 bands. At 1.227 GHz, the measured 3-dB axial ratio beamwidths (ARBWs) are 186° and 187° at $xoz$ and $yoz$ planes, respectively. While the values are 167° and 163° at 1.575 GHz. The measured half-power beamwidths (HPBWs) are both more than 120° at the two bands. The results indicate that the proposed PQHA is a good candidate for UAV GPS applications.

INDEX TERMS Printed quadrifilar helix antenna (PQHA), dual band, GPS, wide beamwidth, miniaturization.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are widely used for exploration, surveillance, data and multimedia communications, and telemetry applications. Recent advances in UAV-related technologies have led to an increasing demand of small, lightweight antennas for communication and navigation [1], [2]. During the operation of UAVs, the position information of the UAV can be obtained by GPS positioning. To receive signals from GPS orbiting satellites, the GPS antenna is required to have right-hand circular polarization (RHCP) and a uniform mode covering the entire upper hemisphere.

In previous researches on GPS antenna, the quadrifilar helix antennas (QHA) are well studied [3]–[6], which usually have good circular polarization (CP) performance. Improved from QHA, printed quadrifilar helix antennas (PQHA) are developed with four radiation elements printed on flexible dielectric substrate [7]–[10]. Generally, the PQHA is composed of four parallel helix-shaped quadrifilar radiation elements, and each radiating element is fed in phase quadrature at the endpoint close to the bottom ground.

In this paper, a low-profile dual-band printed quadrifilar helix antenna (PQHA) with wide beamwidth is presented for UAV GPS applications. The antenna is composed of a hollow dielectric cylinder with four arms of dual-helix metal strips and a hollow dielectric ring with four pairs of circular metal strips. To provide dual-band operation, different lengths of the dual-helix metal strips are applied. By loading the circular metal strips on the dual-helix metal strips, size reduction of the antenna height is realized. Moreover, wide beamwidth is obtained. A miniaturized quad-feed network is also designed to provide equal amplitude signals with sequentially quadrature phases. To validate the proposed structure, a prototype is fabricated. The height of the antenna is 18.5 mm. The experimental results show that good impedance matching ($|S_{11}| < -18$ dB) and axial ratio ($< 2$ dB) are obtained at GPS L1/ L2 bands. At 1.227 GHz, the measured 3-dB axial ratio beamwidths (ARBWs) are 186° and 187° at $xoz$ and $yoz$ planes, respectively. While the values are 167° and 163° at 1.575 GHz. The measured half-power beamwidths (HPBWs) are both more than 120° at the two bands. The results indicate that the proposed PQHA is a good candidate for UAV GPS applications.
with stepped-width arms and dual-faced slot radiation structure are proposed. In [19], by meandering and turning the helix arms into the form of square spirals, size reduction of 43% is obtained. More recently, a miniaturized dual-band spiral PQHA for UAV application is proposed by surface and inner dielectric loading [20]. Although the techniques described above would reduce the antenna’s size, each of these techniques has some specific advantages and limitations with respect to impedance bandwidth, radiation pattern, size and structural strength. In GPS systems, the positioning needs receive signals from at least four satellites. Thus, CP antennas with 3-dB axial ratio beamwidth (ARBW) of larger than 120° and high gain at low elevations are more preferred for better reception of signals no matter whether the satellites are in low or high elevations. However, the features of wide 3-dB ARBW and high gain at low elevations are often ignored by most of the PQHAs.

In the paper, a low-profile dual-band PQHA with wide beamwidth is proposed for GPS L1/L2 applications. It consists of a hollow dielectric ring and a hollow cylinder with metal strips etched on the external surfaces. By loading the hollow dielectric ring on the hollow cylinder as the metal strip supporter, size reduction of the PQHA is realized. Moreover, the beamwidth is also broadened. For verification, a prototype is fabricated and measured. The experimental results show that the advantages of compact structure, good AR, broad beamwidth, high cross-polarization discrimination and low profile are exhibited by the proposed antenna. This paper is organized as follows. Section II presents the proposed PQHA. Section III introduces the implementations followed by a conclusion in Section IV.

II. DESIGN OF THE PROPOSED PQHA
A. ANTENNA CONFIGURATION
The structure of the proposed PQHA is shown in Figure 1. It consists of a hollow dielectric ring and a hollow cylinder with metal strips etched on the external surfaces. By loading the hollow dielectric ring on the hollow cylinder as the metal strip supporter, size reduction of the PQHA is realized. Moreover, the beamwidth is also broadened. For verification, a prototype is fabricated and measured. The experimental results show that the advantages of compact structure, good AR, broad beamwidth, high cross-polarization discrimination and low profile are exhibited by the proposed antenna. The paper is organized as follows. Section II presents the proposed PQHA. Section III introduces the implementations followed by a conclusion in Section IV.

B. EVOLUTIONS OF THE PROPOSED PQHA
The evolutions of the proposed PQHA are shown in Figure 3. Firstly, a traditional PQHA resonated at 1.575 GHz is miniaturized by mounting the hollow dielectric ring on the top of the hollow dielectric cylinder, resulting in the formation of two radiators. For dual-band GPS application, the longer arm is designed at 1.227 GHz and the shorter arm is designed at 1.575 GHz.
is designed, as shown in Figure 3(a) (named as PQHA-I). Each helix arm is designed to be $\lambda/4$ and 1/2 turn. As a result, the width ($w_1$) and length ($l_2 + l_3$) of the arm are optimized as 1.6 mm and 40 mm, respectively, with a radius ($R_2$) of 10 mm. The overall height of the dielectric cylinder ($H_a$) is 30 mm. Figure 4 shows the simulated $|S_{11}|$ and a resonate frequency is observed at 1.575 GHz. However, the impedance matching is not good. To adjust the impedance, four grounding lines are added to each of the helix arm, as shown in Figure 3 (b) (named as PQHA-II). It can be seen from Figure 4 that the $|S_{11}|$ at 1.575 GHz is changed from $-5.5 \, \text{dB}$ to $-18 \, \text{dB}$ by inserting the grounding lines. For PQHA-II, the optimized overall height of the dielectric cylinder ($H_a$) is reduced to 25 mm with ($l_2 + l_3$) of 36.4 mm. The values of $w_1$ and $R_2$ are unchanged. Except of better impedance matching, size reduction is also obtained.

Next, another arm operating at 1.227 GHz is added for dual-band operation, as shown in Figure 3(c) (named as PQHA-III). By tuning the length ($l_1 + l_3$) of the added arm, dual-resonated frequencies can be observed, as shown in Figure 4. The optimized dimensions of ($l_1 + l_3$) are 45.5 mm, and the overall height of the dielectric cylinder ($H_a$) is increased to 32 mm. For further reducing the height of the dual-band antenna, the structure of Figure 3(d) is constructed (named as PQHA-IV). A hollow dielectric supporting ring is mounted on the top of the hollow dielectric supporting cylinder. By etching the circular metal strips on the dielectric ring, the height of the dielectric cylinder is reduced to 18.5 mm for resonating at the same two frequencies. Besides size reduction, wide 3-dB ARBW can also be obtained by using the circular metal strip. Figure 5 shows the simulated ARBW and half-power beamwidth (HPBW) of the four evolution structures at 1.575 GHz. It is observed that by using the circular metal strips, the 3-dB ARBW is enhanced while maintain the same HPBW.

C. PARAMETRIC STUDY OF THE PROPOSED PQHA

Since our design makes use of the circular metal strips to reduce height and enhance the 3-dB ARBW, a parametric study is presented in this section to illustrate the effects. Firstly, the radius of the circular metal strip is investigated. Figure 6 shows the different cases of the circular metal strips. Since the length of the circular metal strip directly affects the resonant frequency, the arm radius $R_3$ and the subtended angles ($\theta_1$ and $\theta_2$) in each case are chosen in such a way...
that all of the different cases resonate at 1.575 GHz and 1.227 GHz. The optimized values of the arm radius \( R_3 \) and the subtended angles \( (\theta_1 \text{ and } \theta_2) \) for each case are also provided in Figure 6. It is observed that to resonate at the same frequency, the values of \( \theta_1 \) and \( \theta_2 \) are decreased with the increasing of \( R_3 \).

Figure 7 shows the simulated gain and AR in the \( \varphi = 0^\circ \) elevation plane for the different cases. It is observed that with the increase of \( \theta_1 \) and \( \theta_2 \), the 3-dB ARBW at the two resonate frequencies are both enhanced. While the changing of the HPBWs are not obvious. In detail, at 1.227 GHz, the 3-dB ARBW for \( \theta_1 = 90^\circ, 130^\circ, \) and \( 170^\circ \) are given by 146°, 164° and 186°, respectively. And the values of HPBW are 114°, 110°, and 112°. At 1.575 GHz, the 3-dB ARBW for \( \theta_1 = 90^\circ, 130^\circ, \) and \( 170^\circ \) are 152°, 169° and 176°, respectively. The values of HPBW for the three cases are all 108°. Thus, larger values of \( \theta_1 \) and \( \theta_2 \) are preferred for wide 3-dB ARBW.

However, it should be mentioned that \( \theta_1 \) can’t be larger than \( 180^\circ \) for avoiding the connection with the dual-helix metal strip.

Secondly, the influence of the distance between the dual-helix metal strip (named as the connecting line \( L_4 \)) is discussed. Since the connecting line \( (L_4) \) is etched on a cylinder, the rotated angle \( \theta_3 \) of the connecting line is utilized as the variable. Figure 8 shows the simulated ARBWs of the PQHA when the value of \( \theta_3 \) is varied in the range of 35° to 55°. The corresponding values of \( L_4 \) are also provided. It is observed from Figure 8(a) that the 3-dB ARBW is nearly constant at 1.227 GHz, which indicates that the distance between the dual-helix metal strips shows less influence on the ARBW at GPS L2 band. While it is found from Figure 8(b) that the 3-dB ARBW at 1.575 GHz is slightly changed with the distance. Widest 3-dB ARBW is obtained at \( \theta_3 = 45^\circ \). When \( \theta_3 \) is less than or larger than 45°, the arm resonated at 1.575 GHz is more closed to the arm resonated at 1.227 GHz. Since small distance enhances the mutual coupling, the radiation at 1.575 GHz will be affected by the adjacent radiation arm. Finally, the value of \( \theta_3 \) is chosen as 45°, and the corresponding value of \( L_4 \) is 5.5 mm. Other parameters are optimized using the HFSS, and the optimal dimensions of the PQHA are listed in Table 1.

**TABLE 1. Dimensions of the proposed PQHA (mm).**

| \( R_1 \) | \( R_2 \) | \( R_3 \) | \( \theta_1 \) | \( \theta_2 \) | \( H_a \) | \( R_a \) |
|---|---|---|---|---|---|---|
| 13.5 | 9 | 4.5 | 170 | 60 | 18.5 | 30 |
| \( W_1 \) | \( L_1 \) | \( L_2 \) | \( L_3 \) | \( L_4 \) | \( L_5 \) |
| 1.6 | 13.3 | 4.4 | 32.8 | 5.5 | 31.4 |

**D. DESIGN OF THE MINIATURIZED FEED NETWORK**

In order to provide equal amplitude signals with sequentially phases of \( 0^\circ, -90^\circ, -180^\circ, \) and \( -270^\circ \), a quad-feed network is designed, as shown in Figure 1(d). It is composed of three Wilkinson power dividers, a 180° phase shifter, and two 90° phase shifters. For UAV Application, the dimensions of the feed network should be as small as possible. Thus, methods of size reduction are applied. Firstly, the BP2G1+ chip working in the range of 1.2 GHz ~ 2.0 GHz is utilized as the
power divider [21]. Secondly, a miniaturized wideband phase shifter is proposed to provide quadrature phases. In general, the topology in [22] is a simple one, which is composed of a main line and a reference line. The main line is realized by a combination of shunt $\lambda/8$ open-/short-ended stubs, while the reference line is a simple straight transmission line. However, the $\lambda/8$ open-/short-ended stubs are still large for limited design area. For further miniaturization, a modified structure of [22] is proposed, as shown in Figure 9.

The main line of the proposed phase shifter is composed of two transmission lines with characteristic impedance of $Z_1$ and electrical length of $\theta_1$, an open-ended stub with characteristic impedance of $Z_2$ and electrical length of $\theta_2$, and a short-ended stub with characteristic impedance of $Z_3$ and electrical length of $\theta_3$. The reference line has a characteristic impedance of $Z_4$ and an electrical length of $\theta_4$. In the following, the design formulas of the proposed phase shifter are derived. Firstly, according to [23], the ABCD matrix of the reference line can be expressed by

$$[A]_R = \begin{bmatrix} \cos \theta_4 & jZ_4 \sin \theta_4 \\ j \sin \theta_4 & \cos \theta_4 \end{bmatrix}$$  (1)

While, the ABCD matrix of the main line is (2a) and (2b), as shown at the bottom of the page.

By converting the ABCD matrices into the scattering matrices, the transmission phase shift of the main line is calculated to be

$$\angle S_{p21} = -\arctan\left[\frac{2Z_1 (Z_1a_1 \sin^2 \theta_1 - \sin 2\theta_1)}{Z_0 (2 \cos 2\theta_1 - Z_1a_1 \sin 2\theta_1)}\right]$$  (3)

and that of the reference line is

$$\angle S_{p43} = -\theta_4$$  (4)

Therefore, the transmission phase difference of the two paths is

$$\Delta \varphi = \theta_4 - \arctan\left[\frac{2Z_1 (Z_1a_1 \sin^2 \theta_1 - \sin 2\theta_1)}{Z_0 (2 \cos 2\theta_1 - Z_1a_1 \sin 2\theta_1)}\right]$$  (5)

To keep ideal impedance matching, the following relation should be satisfied, which is derived from $|S_{p11}| = 0$

$$a_1 = \frac{\sin 2\theta_1 (Z_1^2 - Z_0^2)}{Z_1 (Z_0^2 \cos^2 \theta_1 + Z_1^2 \sin^2 \theta_1)}$$  (6)

Then, substitute (6) into (5), derives (7), as shown at the bottom of the next page.

Using equations (2b), (6) and (7), the circuit parameters of the phase shifter can be obtained. The design procedures are listed below:
1) According to (7), the value of $Z_1$ can be calculated with predetermined $\theta_1$, $\theta_4$ and $\Delta \varphi$.
2) Under the condition of (2b) equals with (6), the values of $\theta_2$, $\theta_3$, $Z_2$ and $Z_3$ can be chosen arbitrarily.

Based on the above design procedure, the $90^\circ$ phase shifter ($\Delta \varphi = 90^\circ$) is firstly designed. The values of $\theta_1$ and $\theta_4$ are predetermined to be $12^\circ$ and $100^\circ$, respectively. The value of $Z_1$ is calculated to be $20.6 \ \Omega$. Then the values of $\theta_2$, $\theta_3$, $Z_2$ and $Z_3$ can be chosen. When choosing, two limitations should be considered. First is the electrical length. Since the area of the feed network is limited, the electrical lengths of the open-/short- ended stubs should be as short as possible. Second is the characteristic impedance. High impedance should not to be chosen for avoiding high fabrication difficulties. Finally, the values of $\theta_2$, $\theta_3$, $Z_2$ and $Z_3$ are chosen as $25^\circ$, $31^\circ$, $70 \ \Omega$, and $70 \ \Omega$, respectively. For the $180^\circ$ phase shifter ($\Delta \varphi = 180^\circ$), the values of $\theta_1$ and $\theta_4$ are predetermined to be $73^\circ$ and $280^\circ$, respectively. The value of $Z_1$ is calculated to be $18.2 \ \Omega$. The values of $\theta_2$, $\theta_3$, $Z_2$ and $Z_3$ are chosen as $19^\circ$, $28^\circ$, $62 \ \Omega$, and $14 \ \Omega$, respectively. Figure 10 shows the simulated results of the $90^\circ$ and $180^\circ$ phase shifters. The amplitude and phase characteristics in the desired frequency band are good enough for the feeding network design.

III. FABRICATION AND MEASUREMENTS

The fabricated photograph of the proposed PQHA is shown in Figure 11. The performance of the fabricated PQHA is measured by PNA network analyzer N5230A and anechoic chamber. Figure 12 shows the measured $|S_{11}|$ of the fabricated PQHA integrated with the feed network. It is seen that the measured $|S_{11}|$ is less than $-10 \ \text{dB}$ in the range of $1.1 \sim 1.65 \ \text{GHz}$. The measured AR and peak gain versus the frequency are shown in Figure 13. It is observed that the AR is less than $3 \ \text{dB}$ in the ranges of $1.15 \ \text{GHz} \sim 1.30 \ \text{GHz}$ and $1.52 \ \text{GHz} \sim 1.60 \ \text{GHz}$. At $1.227 \ \text{GHz}$, the measured gain is 2.9 dBiC, and the value is 3.9 dBiC at $1.575 \ \text{GHz}$. Figure 14 shows the measured radiation efficiency of the fabricated PQHA. It is observed that from $1.15 \ \text{GHz}$ to $1.3 \ \text{GHz}$, the radiation efficiency is more than $60 \ \%$, while from $1.52 \ \text{GHz}$ to $1.6 \ \text{GHz}$, the values are more than $80 \ \%$. At $1.227 \ \text{GHz}$ and $1.575 \ \text{GHz}$, the efficiencies are $75.8 \ \%$ and $89.6 \ \%$, respectively.

In Figure 15, the measured radiation patterns compared to the simulated ones are shown for GPS L2 (1.227 GHz)
FIGURE 14. Measured radiation efficiency of the fabricated PQHA.

and L1 (1.575 GHz) band. It is observed that the patterns in the $xoz$ and $yoz$ planes are similar to each other and the radiation patterns of RHCP is symmetric for the maximum radiation direction. The co-polar (RHCP) field is stronger than the cross-polar (LHCP) counterpart by at least 16 dB over a wide range of elevation angle $\theta$, giving a wide 3-dB ARBW. At 1.227 GHz, the measured HPBW are 128° and 126° for $xoz$ and $yoz$ planes, respectively. While the values are 122° and 120° at 1.575 GHz. Figure 16 shows the simulated and measured ARs of the proposed antenna at the $xoz$ and $yoz$ planes. The measured 3-dB ARBW are 186° and 187° at 1.277 GHz, respectively. While at 1.575 GHz, the corresponding values are 167° and 163°.

Table 2 shows the comparisons between the proposed and previous reported PQHAs. It is observed that by loading the circular metal strips, the proposed antenna shows the lowest height. Besides, wide 3-dB ARBW is also obtained which is usually ignored by other researches. Based on the advantages of low profile and wide beamwidth, the proposed antenna can be a good candidate for UAV GPS applications.

FIGURE 16. Simulated and measured AR. (a) 1.227 GHz. (b) 1.575 GHz.

| Ref. | Freq. (GHz) | Height ($\lambda_0$) | Diameter ($\lambda_0$) | 3-dB ARBW (°) | HPBW (°) |
|------|-------------|---------------------|----------------------|---------------|----------|
| [17] | 1.227/1.575 | 0.33                | 0.18                 | N/A           | 80/73.6  |
| [18] | 1.227/1.575 | 0.35                | 0.12                 | N/A           | 96/122   |
| [19] | 1.14/1.54  | 0.30                | 0.15                 | N/A           | 126/156  |
| [20] | 1.227/1.575| 0.1                 | 0.05                 | N/A           | N/A      |
| This work | 1.227/1.575 | 0.07                | 0.11                 | 186/163       | 126/120  |

$\lambda_0$ is the free space wavelength at 1.227 GHz.

IV. CONCLUSION

In the paper, the design of a low-profile dual-band PQHA with wide beamwidth is presented. The dual-band operation is realized by using the dual-helix metal strips with different lengths. The height of the proposed PQHA is shortened by using the circular metal strips. Moreover, wide beamwidth is also obtained. To provide equal amplitude signals with sequentially quadrature phases, a miniaturized quad-feed network is designed, which is composed of the chip-based power divider and the proposed modified phase shifter. To validate, a prototype working at GPS L1/L2 bands is designed, fabricated and measured. The height of the fabricated PQHA is 0.07$\lambda_0$. At 1.227 GHz, the measured 3-dB ARBW and
HPBW are 186°/187° and 128°/126°, respectively. While the values are 167°/163° and 122°/120° at 1.575 GHz. The results validate the design methods and suggest that the proposed antenna can be a good candidate for UAV applications.

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