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Design, Fabrication, and Tuning Techniques of Quadrifilar Helix Antennas for Small Satellites

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ABSTRACT

Quadrifilar helix antennas are also called fractional turn helix is very appealing to spacecraft applications. A quadrifilar antenna offers circular polarization in its radiating hemisphere and its radiation pattern is not severely affected by a ground plane. These properties are important for closing the communication link and make the antenna relatively independent of the CubeSat frame and mounting location, which facilitates modular design of the antenna.

Although it has similar shape as a helical antenna, a quadrifilar helix antenna is fundamentally different. While there exists design theory and calculators for this type of antennas, detailed notes on design, fabrication, and tuning of different geometries of quadrifilar helix antennas are beneficial for small satellite community. This paper presents design data of several successful demonstrations of quadrifilar helix antennas with different geometries and operation bands.

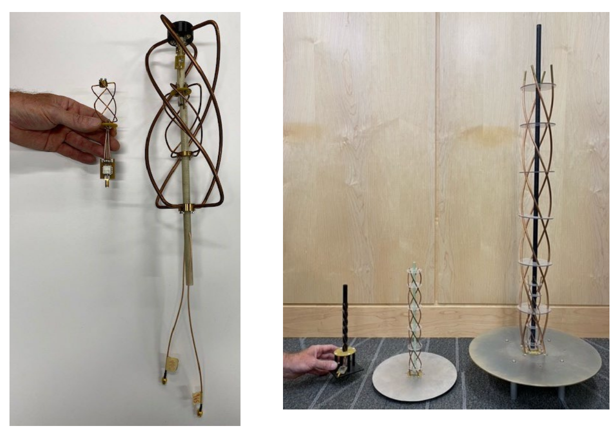
I. INTRODUCTION

A quadrifilar helix antenna (QHA), also called fractional turn helix, is very attractive for small satellite (SmallSat) applications. A QHA offers appealing properties such as circular polarization (CP) in the entire radiating hemisphere, wide beam-width, relatively independent of a ground plane. All of these are important for SmallSat applications— on the aircraft, or as ground station.

Figure 1 shows several QHAs fabricated by the author. Although it resembles helical antennas, a QHA is a fundamentally different type of radiator. Unlike a traveling wave helical antenna, a QHA is a resonant-type antenna and therefore has a limited bandwidth. It also may not need a ground plane as required by helical antennas. Although there exists a large volume of literature on the subject, this paper sticks to the design principles from the original QHA development by Kilgus [1]-[4] and derives terms and design procedure from notes in satellite community [5], [6].

II. TERMINOLOGY

Since the design procedure and terminology of QHA are radically different from other antennas, including helical antennas, it is important to explain the basic nomenclature. QHAs are also called fractional turn helix, which indicates that we will be using terms such as “half-turn”, “1/2 turn”, or “1/4 turn”. The names “turns” and “element” are defined as follows [5].



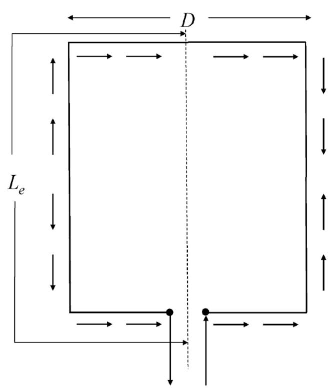
(a) (b)

Figure 1: Examples of QHAs

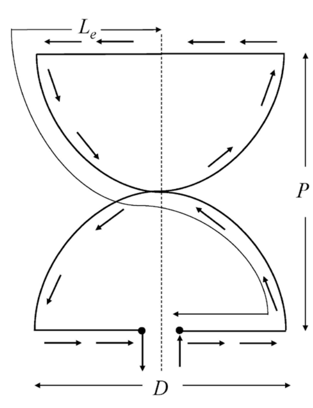
A. Half-turn λ/2 Bifilar Helix

One way of visualizing the half-turn λ/2 bifilar helix, where λ is the wavelength, is to develop it from a continuous quasi-square loop as shown in Figure 2. One could form a loop antenna by feeding this quasi-square loop from the two open terminals at the bottom. The current distribution (only the direction) of a loop of one λ in circumference is indicated by the small arrows in Figure 2-a.

To form a bifilar, imagine inserting a cylinder of diameter D inside the loop. Then, while holding the bottom side of the loop fixed, grasp the top side and give it a half turn (180◦) rotation with the center line (dash line in Figure 2-a) as axis, with respect to the bottom side. As a result of the rotation, each of the two vertical sides of the quasi-square loop becomes a half-turn helix (Figure 2-b) as it curves around the surface of the imaginary cylinder. Because of the curved paths of the once-straight vertical sides, the distance between the top and the bottom is reduced. This distance is called pitch and marked as *P* in Figure 2-b.



(a) A Square Loop Antenna



(b) A 1/2 Bifilar

Figure 2: Forming of a 1/2 Bifilar Helix from a Square Loop

The term element length is defined as the half of the loop and marked as L_e in Figure 2. The helical structure in Figure 2-b is called a bifilar. The name could be understood as being formed by two elements (defined by L_e, *D*, and *P*) shorted together on the top and fed from the terminals at the bottom. Following this naming and forming method, a 1/4 turn λ/2 bifilar is a helix formed by rotating two elements of λ/2 by a quarter turn (90°), a 1/2 turn λ/4 bifilar is a helix formed by rotating two elements of λ/4 by a half turn, and a 1.5 turn 1.25λ bifilar is a helix formed by rotating two elements of 1.25λ/2 by 270°.

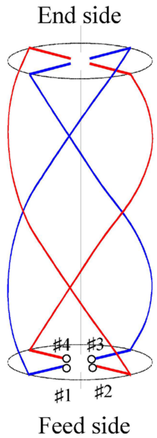
The design parameters, following Kilgus' notations, are diameter *D*, pitch distance *P*, element length L_e, and the axial length (i.e. the length of the bifilar along the helix axis). For a half turn bifilar, the axial length is the same as *P*. For more-turn bifilars, the axial length is determined by the number of turns and pitch. The definition for pitch distance varies among publications and notations, therefore a formula for the axial length from *P* and turns is not provided here, in order not to cause confusion. Once the number of turns, L_e, and *D* are set in a design, the axial length is readily determined.

B. Quadrifilar Helix Antenna

The radiation properties of a bifilar helix antenna are not particularly attractive to many applications. When two bifilar antennas are excited with phase quadrature as shown in Figure 3-a, however, the resulting antenna, called quadrifilar helix antenna, becomes very appealing to spacecraft applications, with properties listed in the instruction part of this paper.

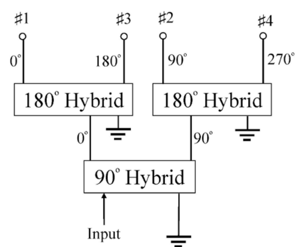
Some additional remarks may be necessary for describing a QHA. A quadrifilar can be formed by any turn and any length bifilar. Let's label the two ends of a quadrifilar helix as feed side, as marked in Figure 3-a. It has been found that the four tips a quadrifilar helix with element length of nλ/2, with n being a natural number, can be shorted together, whereas they need to be kept open circuited for $L_e = (2n-1)\lambda/4$.

A conceptual argument for this open or short arrangement can be made as follows. A bifilar antenna or a square loop in Figure 2-a can be seen as a two-wire transmission line of λ/2 fed from the two terminals. If the end is left open, then the current at the tip and the terminal goes to zero, due to the standing wave formed on the line. This results in a very high input impedance, making it very hard for impedance matching to have an effective radiator. When the two tips are shorted at the end, again a standing wave is formed, but with the current being maximum at the tip and the feed terminal, and a matching can be easily achieved. The voltage at the tip is zero in this arrangement, and therefore one could argue that two pairs of bifilar can be shorted at the tip without interfering with each other. For the λ/4 element length, a similar discussion can be made to see that the tip needs to remain open so that the current at the terminal is not trivial. A more rigorous study can be made by accurately computing the current distribution on a QHA, such as by using method of moments, to analyze the behavior of such an antenna. The discussion here is merely intended for an easy visualization.



Port	Phase
#1	0°
#2	90°
#3	180°
#4	270°

(a) An Illustration of a Quadrifilar Helix Antenna



(b) An Example Feeding Method

Figure 3: Quadrifilar Helix Antenna Formed from Two Bifilar Helices

An example of the feed quadrature is illustrated in Figure 3, where port 1 to 4 lags each other by 90°. Phasing can be achieved by circuits such as illustrated in Figure 3-b. For a QHA with element length of nλ/2, a ground plane is not necessary, whereas for a quadrifilar λ/4 elements, each element behaves like a monopole, and therefore a ground plane is needed for feeding. In this sense, one may find literature or notes using language such as "does not need a ground plane" for a nλ/2 quadrifilar and "must have a ground plane" for a (2n−1)λ/4 type. Figure 4 is an S band 1/2 turn λ/2 QHA, and it is similar to the one described in reference [5]. As seen, the tips of the bifilars are shorted by a metallic disk with screws to allow one to adjust the element length to tune the antenna to the correct frequency.

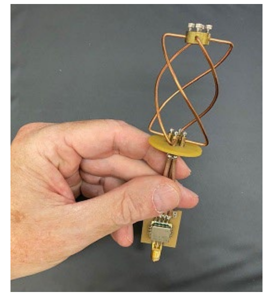


Figure 4: An S band Half-turn λ/2 QHA

III. CHARACTERISTICS OF A QHA

A. Radiation Pattern

It has been discovered that 1/4, 1/2, and 1 turn, λ/2 element-length QHA radiate a cardioid-shaped circularly polarized pattern [1]-[6]. The pattern in Figure 5 is created by the author using a free simulator 4nec2 [7], and it is acceptably close to the pattern described by the Kilgus. It has been reported that an optimal radiation pattern and CP is achieved when $D = 0.18\lambda$ and $P = 0.27\lambda$ [1], [2].

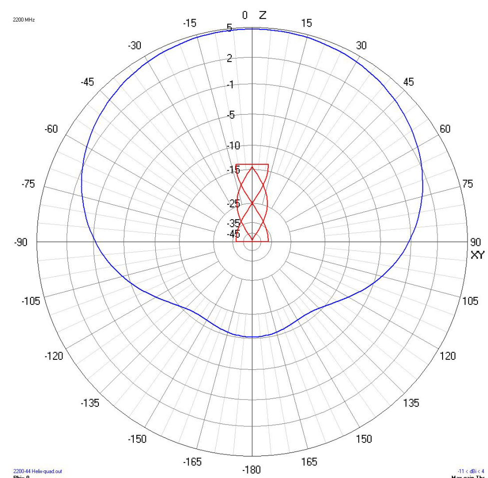


Figure 5: Radiation Pattern of a Half-turn QHA

An interesting property of a QHA occurs when the element is longer than a wavelength and the turn is more than 1. The radiation pattern of such a longer QHA has been found to be shaped into a conical form by optimizing the axial length and turns [3, 4]. The antenna is circularly polarized too. Figure 6 is the pattern of a 400 MHz QHA quadrifilar helix antenna of 1.5 turns and 1.25 λ element length. It is created with 4nec2 by the author. An antenna pattern with wide beamwidth as the one in Figure 6 with CP is very appealing to satellite application because such an antenna helps to maintain an effective communication link for the entire duration when the spacecraft emerges from and goes down the horizon.

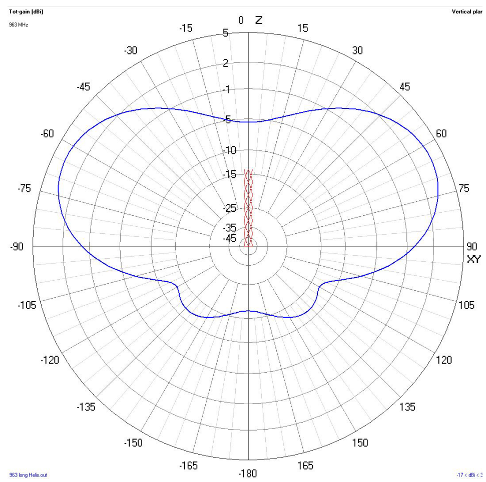


Figure 6: Conical-shaped Pattern of a Multi-turn QHA

B. Effect of the Ground Plane

From section II, it is seen that a QHA formed from half-wavelength elements does not require a ground plane. It has been observed that a QHA, whether it needs a ground plane or not, is not significantly affected by the size and location of a ground plane. An explanation is as follows.

From reciprocity, at a direction where antenna radiates more power density, the antenna receives more power or interference. In another words, at a direction where the radiation pattern has a higher value, then the antenna may receive more power flux or couple in more interference from that direction. Accordingly, if a metallic structure with a size that is comparable to or larger than the size of the antenna, is placed at the vicinity of the antenna, then the structure interferes the most with the antenna when it is placed along the maximum of the radiation pattern, and has the minimal effect when placed along the pattern nulls. When the structure is far from the antenna, then the electromagnetic field radiated by the antenna is low upon reaching the object, and the reflected amplitude is accordingly low.

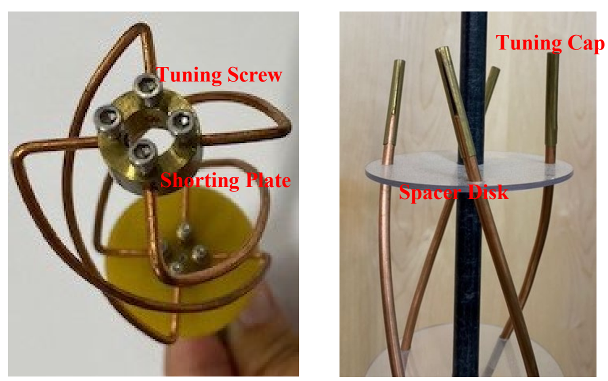
Both cardioid and conical shaped radiation patterns of QHA have relative low back lobes. Therefore, from the principle of reciprocity, one could conclude that a quadrifilar antenna is relatively independent of its mounting location on a satellite.

These properties can be easily verified through simulations and experiment, and is very helpful for a modular design where one could create a QHA without worrying much about whether it will be mounted on the middle of edge of a spacecraft.

IV. QHA EXAMPLES

Several QHAs have been designed and fabricated by the author. Figure 1 shows some of those prototypes, where (a) shows half-turn λ/2 QHAs at 2200 and 400 MHz respectively, and (b) shows three 1.5 turn QHAs formed from 1.25λ elements operating at 2200, 960, and 400 MHz respectively.

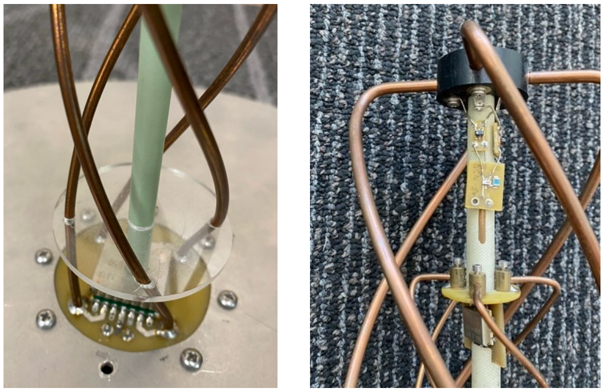
For practical tuning purpose, a metallic plate and tuning screws where used for λ/2 QHAs (Figure 7-a), whereas brass caps were utilized for QHAs formed from λ/4 Elements (Figure 7-b). The screws allow one to push in or pull out the tips of the bifilars to tune it to the right frequencies and then short them together. Moving the caps up and down does the same purpose for the open-tipped QHAs. It has been found that the tuning cap is a more convenient and practical method, and therefore the longer and multi-turn QHAs built by the author were of open-tip geometry.



(a) (b)

Figure 7: Tuning Mechanisms

The phasing of the QHA elements were illustrated in Figure 3. The QHAs built by the author used off-the-shelf mini-circuits ([8]) quadrature parts (Figure 8-a), or a 90° hybrid with balun transformers (Figure 8-b). The latter is another implementation of achieving phase quadrature and the circuit illustration is presented in Figure 9 for easy referencing. For multi-turn $L_e > \lambda$ QHA, spacing disks were placed to hold the helical shape (Figure 8-a). The disks can be made from any dielectric material. The ones in Figure 1 and 8 are machined from Lucite glass.



(a) (b)

Figure 8: Tuning Mechanisms

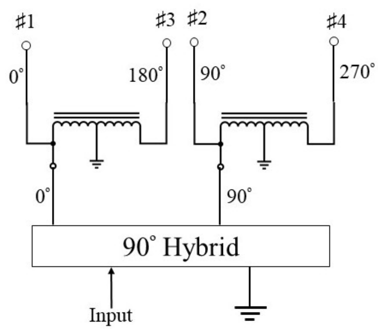


Figure 9: An Alternative Feeding Method

IV. APPLICATION NOTES AND CONCLUSIONS

Both a half turn and multiple turn quadrifilar are circularly polarized and therefore stand as favorable antenna solutions for spacecrafts. A half turn 0.5λ quadrifilar helix antenna is slightly longer than a quarter wavelength, with a diameter smaller than 0.1 wavelength. It is circularly polarized and has a smaller size compared to two orthogonal dipoles for a CP. For lower frequencies where one cannot use a patch antenna, a QHA may become a good choice as a low profile antenna. A longer and more turn quadrifilar helix allows one to optimize the radiation pattern to form a conical shape, that is beneficial in reducing the pointing loss in satellite communication links.

The challenge of having quadrifilar antennas on a SmallSat lies on its footprint and deployment. Successful implementation of this type of antenna on small spacecrafts include the S band QHA developed at Surrey Satellite Technology [9] and ones at European Space Agency [10]. There are also emerging developments of deployable QHAs [1] and commercial prototypes suitable for CubeSats [12].

It should be noted that QHAs are not limited to implementation on spacecraft. They are suitable for ground stations. There are applications where multi-band QHAs are required. In that case, careful stacking of QHAs operating at different frequency is a good solution. Nesting different bands as shown in Figure 1-a and Figure 8-b has been tried but did not yield effective QHAs, due to strong coupling between the elements. From the reciprocity principle explained in section III-B, it is seen that a QHA with conical pattern (Figure 6) has a relative low coupling on the front and back sides. Therefore, stacking multiple QHAs along their axis is as illustrated in Figure 10 is a feasible solution.

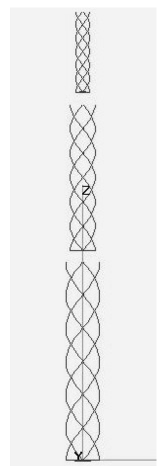


Figure 10: Illustration of Multi-band Stacking

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