QFHA Antennas for Satellite Radio and Mobile Phone Applications

Quadrifilar helical antennas (QFHA) are one of the best candidates to provide a high gain, shaped beam with excellent circular polarization axial ratio for satellite radio and mobile satellite phone systems. One of the most compelling reasons to use these antennas for digital radio and mobile satellite systems is their ability to shape the beam so as to provide more gain in the regions where the satellite is between the horizon and the zenith. Depending on the satellite constellation orbital design, a dip in the antenna gain pattern could be tolerated when the satellite is overhead, because the slant range is minimized. Although there are other approaches to the development of these types of patterns, such as planar microstrip, stacked elements and array antennas, their ability to shape the radiating beam is much more restricted, and their implementation may actually become more bulky due to the requirements of grounding back cavities.

The QFHA is a vertical antenna, but it can be designed to be low profile, and perhaps retractable, especially for applications in the more compact hand-held mobile satellite systems. For the satellite radio systems, the antennas are primarily used on the roof of the vehicles. It is likely that these antennas will be preinstalled in future automobile models. For mobile satellite phones, however, the hand-held units will be the most likely beneficiaries of these antennas. The mobile satellite phone systems for automobiles could also require a similar antenna mounting on the top of the vehicles.

Although the bandwidth for the satellite radios is less than one percent, the bandwidth for the mobile satellite radios could be much greater. Furthermore, the transmit and receive bands are separate. For example, L-band for up-link and S-band for down-link are used for CDMA-based systems, and L-band up- and down-links for TDMA systems (1610.0 to 1626.5 MHz and 2483.5 to 2500.0 MHz for CDMA systems, and about half in L-band for the TDMA systems).

In order to provide a circular polarization with excellent axial ratio, a relatively precise beam forming network (BFN) is required to provide the four outputs with 0°, 90°, 180° and 270° phase-shift (called BFN90). In this article, a specific QFHA design for satellite radios is presented, along with a planar design for an integrated BFN90. The BFN is de-
QFHAs are rather unique in their ability to provide very low axial ratio right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP) with high gain and shaped pattern. As the name implies, QFHAs are primarily based on helical antennas. A single helical antenna is capable of operation in two primary modes: normal and axial. Some of the design parameters for the single helix are the pitch angle and number of turns, most often described by a triangle, with the tangent of the angle \( \alpha \). Since the QFHA is primarily constructed of four interleaved helical antennas, spatially rotated 90° and also fed with 90° incremental (or decremented, for the opposite sense CP), its design is primarily based on the helical antenna design.

Although single helical antennas require a relatively large ground plane, and more stringent impedance matching design, the QFHA provides a very desired feature of less dependency on the ground plane due to phasing, pitch angle and other factors. Some of these features provide a greater incentive for using a QFHA versus a single helical antenna. Furthermore, experiments seem to support that there are more degrees of freedom in the pattern shaping of the QFHA than in single helix antennas.

Primarily, it is possible to design a QFHA to operate at the two extremes: in the normal mode, with a radiation pattern similar to a dipole, or in an axial mode, with an end-fire radiation pattern similar to the pattern of an end-fired linear array. Furthermore, by parametric variations, it is possible to design a QFHA antenna to operate at some intermediate stages between these two extreme pattern modes.

Identifying the affecting parameters that lead to a desired pattern shape is the challenging aspect of the development, and one that requires a combination of computer aided design (CAD) and experimentation. A limited number of experimental design curves, applicable to a few cases, can be found in the literature; however, a combination of starting points from these curves and iterative CAD tools based on method of moment (MoM) was utilized to develop the antenna which is presented in this article.

Overall, experience shows that it is possible to develop a very high performance QFHA with excellent impedance matching over a wide bandwidth if the antennas are developed based on the traveling wave theory. This usually requires careful design of the antenna radius, pitch angle and height, which will control the phase velocity and current distribution over the antenna structure. The ability to fine-tune the percentage of the antenna’s behavior between the normal and axial modes will determine how finely one can develop a specific shaped pattern. This process may be very tedious to carry out in the traditional ways, but is much more attuned to the modern approach of CAD and optimization. At the time of the development of the original design, the optimization based on pattern shaping was unavailable. Today, however, it is much more feasible. A systematic formulation for the determination of the pattern shape based on the physical parameters could be developed in the form of some mathematical derivations, which could prove very challenging. If such a formulation existed, it could provide a new breakthrough in the way QFHA antennas are designed and optimized. Such a formulation development could be the subject of a very useful graduate thesis or dissertation, and could open up new ways of using the functionalities of the QFHA. The trick is all in strategic phase and amplitude relationship of the two modes, and other higher modes yet to be identified. A newly developed counter-wound toroidal helical antenna is just one example of a possible variation to the basic helical antenna theory.

The QFHA design featured here is an antenna with 1.5 turns, 4” length and a diameter of 0.750”. To obtain this diameter, however, various diameters were simulated. Figure 1 shows the calculated radiation pattern for some QFHAs with different diameters ranging from 0.700” to 0.884”. Before getting to this design, numerous parametric designs were also simulated and optimized. The choices of the present parameters were made when it appeared that an optimal performance could be achieved. After this design was constructed, the measured results indicated that the center dip is too deep. Other designs were tested to bring the dip up, involving changing the diameter of the antenna tube. From the measurement, it appears the optimum choice was for a QFHA with a diameter of 0.750”. Most efforts were made to obtain a standard tube size for manufacturing purposes. The predicted performance is for the QFHA placed on an infinite ground plane.

The measured results for the QFHA with a diameter of 0.750” on a 16” × 16’” finite ground plane are shown in Figure 2 for three frequencies. The rotating linear probe method was used to measure the radiation pattern of this QFHA for circular polarization. The lower traces show the actual rotating linear data, where the smaller ripples correspond to smaller axial ratio for circular polarization. The upper traces correspond to the radiation pattern for the

![Figure 1 Theoretical elevation patterns for a QFHA with 1.5 turns and 4 inch length; (a) overall pattern and (b) zoomed near the maximum peak.](image-url)
The plot scale is adjusted for the three frequencies of interest to show the actual maximum LHCP gain in dBi. Much care was taken to reduce extraneous radiations from cables and other sources in the anechoic chamber. Although much care was given to isolate and remove most sources of error in the chambers, there may be some minimal errors that could not be accounted for. This is one reason that there appears to be some discrepancies between the predicted pattern and the measured pattern, especially at the 90° crossing. The measured pattern seems to be slightly wider than calculated.

To feed the QFHA, a planar beam forming network was also designed. Figure 3 shows a microstrip CAD layout of the QFHA beam forming network. BFN90. The ports in the central area, identified as 3, 4, 5 and 6, provide 90° incremental phasing with equal power distribution for each helix of the QFHA. As illustrated, this design is fabricated on a low dielectric constant material k = 3, such as Rogers 4003. The size of a useable BFN90 circle is approximately 1.5° in diameter, and can be reduced to a smaller size, nearer to the 0.750° diameter of the QFHA, by using substrates with higher dielectric or by multi-layer circuit technologies. This approach was selected to allow the use of empty areas where other electronic components of the receiver could be accommodated on the same substrate, around and in the vicinity of the BFN90. Furthermore, plans for inclusion of a circular, or square microstrip patch antenna, was considered to allow incorporation of an integrated linear polarized antenna for terrestrial repeater reception for the satellite radio. A monopole, or a sleeved dipole extended out from the center of the QFHA antenna tube, was also tried and worked well only if it was completely on top of the winding, clearing the QFHA tube. If the monopole/dipole was even partially inside the tube, the QFHA performance was unchanged, but the monopole/dipole performance was affected by the QFHA winding proximity and parasitic currents, which were induced or otherwise flowed. This method unnecessarily increases the length of the overall antenna and the radome. The microstrip approach preserves the length of the combination antenna systems to that of the QFHA tube.

The CAD of the BFN90 was carried out using the MoM. Some partial results of the simulation are shown in Figure 4. The Smith chart shows the calculated phasing distribution of the BFN90, with the sense of 90° increment or decrement to allow LHCP or RHCP polarization. The choice of polarization sense depends on the direction of the helical winding. The Smith chart displays the S-parameters from the input port 1 to the output ports 3, 4, 5 and 6. The fact that the points appear to be almost exactly 90° apart shows that the design is working well. The experimental data showed excellent agreement with the theoretical design.

Figure 5 shows the insertion loss and return loss of the BFN90. It shows the expected –6 dB division factors and the predicted input port return loss of nearly –24 dB. As one expects, any increase over –6 dB division factor (divide by four) corresponds to the true insertion loss of the BFN90, which the theory indicated to be approximately 0.25 dB on the average. The measured data turned out to be approximately 0.35 dB on the average, including the two connectors losses.

In addition to the insertion loss of the BFN90, the differential phase between consecutive output ports is also calculated and is shown in Figure 6. The experimental results of the actual
fabricated BFN90 showed excellent agreement with the calculated data. The measured differential phases between the four ports were within ±1° over the entire band of interest. This will provide for a very low axial ratio in the final assembly of the QFHA, as was evident from the excellent measured pattern plots.

All of the performance data shown above are for the band of 2.320 to 2.332 GHz. To ensure that the behavior of the BFN90 is as expected over a wider bandwidth, a wider frequency sweep was simulated. Figure 7 is the theoretical broadband plot for the BFN90, showing the expected behavior of the hybrid, which can be used for a larger bandwidth than the present design range. This can be useful for applications such as mobile satellite antennas, which require a larger bandwidth of operation.

Various parts of the QFHA antennas were fabricated to develop several prototypes for measurement and experimentation. Photographs of some of these prototypes are provided here. Figure 8 shows the fabricated BFN90 network, with top and bottom views of the substrate. Figure 9 shows parts of several experimental QFHA antennas and some partial assemblies. The QFHA starts from planar Mylar or flexible printed circuit board rolled into a cigar-like tube as shown. Other methods are also possible, which may be used for mass manufacturing. The BFN90 feeding substrates are also shown. Figure 10 shows some finished QFHA prototypes with the integrated BFN90 feed units and connectors in preparation for pattern testing.

The planar distributed nature of the BFN90 reduces the length of the QFHA antenna and allows sharing the unused real estate for other components and to further decrease the size. The measurements were sensitive to the phase centering, and when using the local small ground plane, proper positioning of the antennas was very difficult, and repeatability was low. However, with the larger 16” × 16” ground plane, it worked better.

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