Research Article

Dual-Band Operation of a Circularly Polarized Four-Arm Curl Antenna with Asymmetric Arm Length

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This paper presents dual-band operation of a single-feed composite cavity-backed four-arm curl antenna. Dual-band operation is achieved with the presence of the asymmetrical arm structure. A pair of vacant-quarter printed rings is used in the feed structure to produce a good circular polarization (CP) at both bands. The cavity-backed reflector is employed to improve the CP radiation characteristics in terms of the 3-dB axial ratio beamwidth and broadside gain. The proposed antenna is widely applicable in dual-band communication systems that have a small frequency ratio. Examples of such a system are global positioning systems.

1. Introduction

Curl antennas, which are formed by short single-arm Archimedean or rectangular spirals, have been developed as small, low-profile, circularly polarized (CP) radiation elements [1–12]. Antennas of this kind are mechanically simple and produce CP radiation with a single-feed without the need for an external circuit. A conventional curl antenna, which is placed approximately a quarter-wavelength above a large ground plane, can provide good impedance matching and good CP radiation over a bandwidth of approximately 10% [1–8]. However, these antennas have several drawbacks, such as a slight tilt in the broadside radiation pattern due to their single-arm configuration, the need for a large ground plane, and their limitation to single-band operation. Recently, single-feed four-arm curl antennas have been reported for CP radiation to improve the performance of conventional curl antennas [13, 14]. These curl antennas yield single-band CP operation with the same arm length. A dual-band operation can be achieved by dividing the antenna's arms into two branches of different lengths [15]. However, this approach leads to very complicated antenna configuration in the design process.

This paper describes a simple method to design dual-band operation of a four-arm curl antenna. Dual-band operation is obtained by creating different arm lengths in

the four-arm curl structure. The antenna is optimized for global positioning system (GPS) L1 and L2 bands. The resulting antenna was first characterized with the ANSYS High-Frequency Structure Simulator (HFSS) and then confirmed by experiments. The final design, with an overall size of $90 \times 90 \times 30 \text{ mm}^3$ ($0.3681\lambda_0 \times 0.3681\lambda_0 \times 0.1227\lambda_0$ at the GPS L2 frequency), yields $|S_{11}| < -10 \text{ dB}$ bandwidths of 1.217–1.234 GHz and 1.495–1.595 GHz and AR < 3 dB bandwidths of 1.220–1.230 GHz and 1.565–1.600 GHz. Additionally, the antenna radiates a wide-beam right-hand circular polarization (RHCP) with high radiation efficiency at both bands. In comparison with the dual-band multiarm curl GPS antenna [15], the proposed antenna has a much simpler structure, smaller size, and comparable $|S_{11}|$ and AR bandwidths.

2. Antenna Geometry

Figure 1 shows the geometry of the proposed antenna that is composed of a four-arm curl radiator, a coaxial line, and a reflector. The curl radiator, which is a four-arm Archimedean spiral antenna with a small number of turns, was built on both sides of a circular Rogers RO4003 substrate with a radius of R_{sub} , a relative permittivity of 3.38, a loss tangent of 0.0027, and a thickness of h_s . Two arms (orange color) were placed on the top of the substrate whereas the other two arms (grey

FIGURE 1: Geometry of the proposed antenna: (a) cross-sectional view with the cavity-backed reflector and (b) top view of radiator.

color) were on the bottom of the substrate. The curl arm was characterized by the Archimedean spiral drawing function of the HFSS software [16], which is defined by a center position of $(0, 0, 0)$, a direction vector $(0, 0, 1)$, a starting point of R_0 , a radius change of R_c , a number of turns of n_i ($i = 1, 2, 3, 4$), and a stripline width of W_s . The radiator is fed by a vacant-quarter printed ring, which helps the antenna to be directly matched to a 50Ω coaxial line over a broad bandwidth and produces the CP radiation. The reflector is a rectangular box with base dimensions of $W \times W$ and a height of H_c . To achieve the dual-band operation, the asymmetrical curl arm structure was created by choosing a different number of turns (n_i) for different arms.

3. Mechanism of Dual-Band Operation

As mentioned above, the dual-band operation of the proposed antenna is obtained by choosing a different number of turns for different arms. To demonstrate this, the input impedances (Z_{11}) of an ideal four-arm curl antenna [13] are examined for symmetric and asymmetric configurations via the HFSS simulation. Figure 2 shows the HFSS simulation

FIGURE 2: HFSS simulation modeling for an ideal four-arm curl antenna in free space: (a) top view and (b) side view.

modeling of the ideal four-arm curl antenna. The arms were placed on both sides of a 40 mm radius Rogers RO4003 substrate with a thickness of 0.508 mm. The orange arms (#1 and #3) were on the top of the substrate and the grey arms (#2 and #4) were on the bottom of the substrate. Referring to Figure 1(b), the arm was formed by a center position of $(0, 0, 0)$, a direction vector $(0, 0, 1)$, $R_0 = 9$ mm, $R_c = 25$ mm, $n = 1$, and $W_s = 3$ mm. The antenna was simulated by assuming two excitation sources (port-1 for the orange arms and port-2 for the grey arms) and their input impedances (Z_{11} or Z_{22}) were calculated for three configurations. Case #1: $n_1 = n_2 = n_3 = n_4 = 1$, case #2: $n_1 = n_2 = 0.9$ and $n_3 = n_4 = 1$, and case #3: $n_1 = n_2 = 1.1$ and $n_3 = n_4 = 1$. The results were given in Figures 3–5. Since the Z_{11} value is the same as Z_{22} and expresses the input impedance of the ideal four-arm curl antenna, and Figures 3–5 only show the real and imaginary parts of Z_{11} values for the three cases.

As shown in Figure 3, the symmetrical four-arm curl antenna behaves as a resonant antenna in the low-frequency range, whereas the antenna behaves as a traveling wave antenna in the high-frequency region with an almost stable input impedance value. The resonance was defined as the frequency at which the imaginary value of Z_{11} is zero. With the chosen parameters, the antenna yielded two resonances in the interest frequency range. The first one was 1.58 GHz with an input resistance of approximately 50Ω while the second was 1.79 GHz with an input resistance of approximately

FIGURE 3: Simulated input impedance (Z_{11} or Z_{22}) of the ideal symmetrical four-arm curl antenna ($n_1 = n_2 = n_3 = n_4 = 1$).

FIGURE 4: Simulated input impedance (Z_{11} or Z_{22}) of the ideal asymmetrical four-arm curl antenna ($n_1 = n_2 = 0.9$, $n_3 = n_4 = 1$).

290 Ω . In the high-frequency region, the real part of Z_{11} was nearly constant with a value of 60 Ω , while the imaginary part of Z_{11} was nearly constant with a value of -90 Ω . For convenience, resonance with $\sim 50 \Omega$ of resistance is called usable resonance, while resonance with a high resistance is called nonusable resonance. This result indicates that the antenna can be well matched to a 50 Ω source without the need for an external circuit at its first resonance.

To create the asymmetrical four-arm curl antennas, the number of turns for arms #1 and #2 was varied while the other arms (#3 and #4) were fixed. Figure 4 shows the Z_{11} values of an asymmetrical four-arm curl antenna with $n_1 = n_2 = 0.9$ and $n_3 = n_4 = 1$. The antenna yielded more resonances compared to the symmetrical one. Two

FIGURE 5: Simulated input impedance (Z_{11} or Z_{22}) of the ideal asymmetrical four-arm curl antenna ($n_1 = n_2 = 1.1$, $n_3 = n_4 = 1$).

resonances at 1.605 and 1.995 GHz can be used because the real values of Z_{11} nearly equal 50 Ω . The Z_{11} values of the other asymmetrical curl antenna ($n_1 = n_2 = 1.1$ and $n_3 = n_4 = 1$) are shown in Figure 5. The antenna yielded two resonances at 1.375 GHz and 1.705 GHz with the real value of Z_{11} approximately 50 Ω . These results indicate that both asymmetrical configurations of the four-arm curl antenna yielded a dual-frequency operation in the frequency band of interest. To have a CP wave, the two sources of excitation in Figure 2(b) must have equal amplitudes and a 90° phase difference. Consequently, the antenna requires a one-to-two power combiner/splitter and a 90° phase shifter in the feeding structure. This approach complicates the antenna design and fabrication.

To generate the CP radiation with a single-feed, the asymmetrical four-arm curl antennas are incorporated with a pair of vacant-quarter printed rings, as shown in Figure 6. The rings were designed with a 5.4 mm radius and a 1 mm width. Due to the presence of the rings, the antenna geometry was slightly changed compared to the ideal configurations; that is, arms #1 and #4 with a number of n_t were placed on the top of the substrate whereas arms #2 and #3 with a number of n_b were placed on the bottom of the substrate. The other design parameters of the antenna were the same as those of the ideal structure in Figure 2. To reconfirm the dual-band operation of the asymmetrical configuration, the $|S_{11}|$ and AR values of the antenna were calculated for different n_t and given in Figure 7. For the symmetrical case ($n_t = n_b = 1$), the antenna yielded only the operational band near the GPS L1 frequency. For the asymmetrical case ($n_t = 0.9$ and $n_b = 1$), the antenna yielded a dual-band operation near 1.7 GHz and 2.1 GHz. For the other asymmetrical case ($n_t = 1.1$ and $n_b = 1$), the antenna yielded a dual-frequency occupied at 1.42 GHz and 1.79 GHz. For both asymmetrical cases, the upper bands were divided by an undesired notch, which could be attributed to the trapping electromagnetic energy between the adjacent

FIGURE 6: Four-arm curl antenna fed by double vacant-quarter printed rings [8]: (a) top view and (b) side view.

arms. This notch can be eliminated by adjusting the width of the curl arm. Furthermore, the identical behaviors of the dual-band operation were obtained when $n_t = 1$ is fixed and n_b is varied, and, therefore, their results are not shown.

It is well known that the resonances of the curl antenna can be easily controlled by the number of turns, the spacing between turns, and the width of the arm, as well as the dielectric substrate (permittivity and thickness). Also, CP radiation can easily be achieved by adjusting the ring configurations. Accordingly, the asymmetrical four-arm curl antenna was optimized for good impedance matching and CP radiation at the GPS L1 and L2 frequencies. Note that without the reflector, the four-arm curl antennas radiate a bidirectional electromagnetic wave at their operational frequencies. To achieve a desired broadside pattern at both bands, a cavity-backed reflector with the base dimensions of $90 \times 90 \text{ mm}^2$ ($0.3681\lambda_0 \times 0.3681\lambda_0$ at the GPS L2 frequency or $0.4725\lambda_0 \times 0.4725\lambda_0$ at the GPS L1 frequency) and a height of 30 mm ($0.1227\lambda_0$ at the GPS L2 frequency or $0.1575\lambda_0$ at the GPS L1 frequency) was employed in the antenna. Referring to Figure 1(b), the parameters of the final design are as follows: $R_c = 27 \text{ mm}$, $R_0 = 9.7 \text{ mm}$, $R_r = 6 \text{ mm}$, $W_r = 1 \text{ mm}$, $W_b = 6 \text{ mm}$, $W_s = 4.5 \text{ mm}$, $h_s = 0.508 \text{ mm}$, $H = 30 \text{ mm}$, $H_c = 30 \text{ mm}$, $n_1 = 1.198$, $n_2 = 1.185$, $n_3 = 1.044$, and $n_4 = 1.035$. To demonstrate the effects

FIGURE 7: Simulated (a) $|S_{11}|$ and (b) AR values of the four-arm curl antenna shown in Figure 6 for different n_t ($n_b = 1$ was fixed).

of the cavity on AR performance, the $|S_{11}|$ and AR values of the dual-band asymmetrical four-arm curl antenna in different configurations, including those in free space and at different heights of the cavity, were calculated and are shown in Figure 8. The cavity-backed antenna yielded a narrower impedance bandwidth, but significantly better CP performance compared to the case in free space. With an increase of H_c , the resonance and CP center frequencies of the antenna decreased at both operating frequencies, and the AR characteristic improved significantly. For $H_c = 30 \text{ mm}$, the simulations resulted in good impedance matching and CP radiation at both bands. Its impedance bandwidths were 1.220–1.235 GHz and 1.510–1.605 GHz for $|S_{11}| < -10 \text{ dB}$, and

FIGURE 8: Simulated (a) $|S_{11}|$ and (b) AR values of the asymmetrical four-arm curl antenna in different configurations.

FIGURE 9: Simulated 3D total-gain pattern of the cavity-backed asymmetrical four-arm curl antenna with $H_c = 30$ mm: (a) GPS L1 and (b) GPS L2 frequencies.

its 3-dB AR bandwidths were 1.222–1.232 GHz and 1.570–1.605 GHz with two CP center frequencies at 1.227 GHz (AR = 0.66 dB) and 1.580 GHz (AR = 1.13 dB). As shown in Figure 9, the antenna yielded an excellent unidirectional radiation pattern at both bands. The simulations resulted in a gain of 6.9 dBi and a radiation efficiency of 97% at the GPS L1 frequency but a gain of 6.7 dBi and a radiation efficiency of 91% at the GPS L2 frequency.

4. Measurements

For verification, the dual-band asymmetrical four-arm curl GPS antenna was realized and measured. The radiator was built on both sides of a Rogers RO4003 substrate with

a copper thickness of $17 \mu\text{m}$ via a standard wet-etching technology. The reflector was constructed from five copper plates (one $90 \times 90 \text{ mm}^2$ and four $90 \times 30 \text{ mm}^2$) with a thickness of 0.2 mm. Figure 11 shows the measured and simulated $|S_{11}|$ and AR values of the fabricated prototype (Figure 10). The measurements resulted in a $|S_{11}| < -10$ dB bandwidth of 1.217–1.234 GHz and 1.495–1.595 GHz and a 3-dB AR bandwidth of 1.220–1.230 GHz and 1.565–1.600 GHz with two CP center frequencies at 1.225 GHz (AR = 1.22 dB) and 1.590 GHz (AR = 0.7 dB), respectively. These measurements agreed quite closely with the HFSS predictions.

Figure 12 shows a comparison of simulated and measured gain patterns for the fabricated antenna at the GPS L1 and L2 frequencies. The measured results are in good agreement with

FIGURE 10: Top view of the fabricated dual-band GPS antenna.

FIGURE 11: Measured and simulated (a) $|S_{11}|$ and (b) AR values of the fabricated antenna.

the HFSS simulation. The antenna yielded an RHCP radiation with wide beam and symmetrical profiles at both bands. At the GPS L1 frequency, the measurements resulted in a gain of 7.0 dBic, a front-to-back ratio of 18 dB, and half-power beam width (HPBW) of 82° and 84° in the x - z and y - z planes, respectively. At the GPS L2 frequency, the antenna yielded a gain of 6.7 dBic, a front-to-back ratio of 15 dB, and HPBW of 92° and 82° in both x - z and y - z planes, respectively. As shown in Figure 13, both simulations and measurements resulted in a broad 3-dB AR beamwidth ($>120^\circ$) at two frequencies. Additionally, the measured radiation efficiencies were 95.0% and 87.0% at the GPS L1 and L2 frequencies, respectively.

Table 1 shows the comparison of the measured performance of the proposed antenna with that of the dual-band multiarm curl GPS antenna [15]. The proposed antenna yielded a simpler configuration, a smaller size, and comparable operational bandwidths. Table 2 shows a comparison of the measured performance of the proposed antenna and

those of previous single-feed dual-band GPS antennas [17–23]. It is observed that the proposed antenna yielded a significantly wider 3-dB AR beamwidth at both bands as compared to the other antennas.

5. Conclusion

A composite cavity-backed four-arm curl antenna has been developed for dual-band operation by creating an asymmetrical arm structure. The antenna with overall dimensions of $90 \times 90 \times 30 \text{ mm}^3$ ($0.3681\lambda_0 \times 0.3681\lambda_0 \times 0.1227\lambda_0$ at the GPS L2 frequency) resulted in a $|S_{11}| < -10 \text{ dB}$ bandwidth of 1.217–1.234 GHz and 1.495–1.595 GHz and a 3-dB AR bandwidth of 1.220–1.230 GHz and 1.565–1.600 GHz. Furthermore, the antenna radiates wide-beam RHCP ($>120^\circ$) and operates with high radiation efficiency ($>85\%$) at both bands. With many advantages, such as compact size, good CP radiation, wide-beam, and high radiation efficiency, this antenna is a good

TABLE 1: Performance comparison of dual-band multiarm curl antennas.

Antenna structure	Overall size (mm ³)	Arm number	$ S_{11} $ BW (GHz)	AR BW (GHz)	Gain (dBic)	RE (%)
Proposed	$90 \times 90 \times 30$	4	1.217–1.234	1.220–1.230	6.0	87.0
			1.495–1.595	1.570–1.605	7.0	95.0
Ref. [15]	$100 \times 100 \times 30$	8	1.221–1.282	1.212–1.240	7.3	88.4
			1.545–1.660	1.560–1.590	7.5	92.0

FIGURE 12: Radiation patterns of the dual-band GPS antenna at (a) GPS L1 and (b) GPS L2 frequencies.

TABLE 2: Performance comparison between the proposed antenna and the previous single-feed dual-band GPS antennas.

Antenna structure	Overall volume (mm ³)	-10 dB $ S_{11} $ bandwidth (GHz)	3 dB AR bandwidth (GHz)	Max. gain (dBic)	Max. 3 dB AR beamwidth	Radiation efficiency (%)
Proposed antenna	90 × 90 × 30	1.217–1.234 1.495–1.595	1.220–1.230 1.570–1.605	6.0 7.0	160° 176°	87.0 95.0
Ref. [17]	Exact values not specified	1.2195–1.2345 1.5625–1.875	1.217–1.235 1.567–1.597	2.9 5.5	Exact values not specified	Exact values not specified
Ref. [18]	115 × 115 × 21.5	1.103–1.297 1.444–1.636	1.195–1.280 1.568–1.577	5.0 2.0	~90° ~60°	Exact values not specified
Ref. [19]	(60) ² × π × 20	1.222–1.232 1.563–1.587	1.225–1.229 1.572–1.578	5.36 6.20	86° 52°	71.1 79.2
Ref. [20]	100 × 100 × 20	1.190–1.235 1.565–1.585	1.220–1.231 1.572–1.581	1.5 3.0	~100° ~100°	80.7 86.5
Ref. [21]	120 × 120 × 40	1.188–1.265 1.453–1.800	1.217–1.240 1.525–1.630	6.3 7.5	140° 152°	90.0 97.4
Ref. [22]	76 × 52 × 20	1.200–1.250 1.545–1.600	Exact values not specified	3.0 2.5	~50° ~50°	63.5 67.8
Ref. [23]	85 × 85 × 11.5	1.202–1.706	1.205–1.240 1.530–1.625	5.28 5.35	94° 108°	91.3 93.9

FIGURE 13: Axial ratio as a function of theta angle: (a) GPS L1 and (b) GPS L2 frequencies.

candidate for dual-band applications with a small frequency ratio.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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