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A New Observation in Spiral and Curl Antenna Configurations above the Ground Plane

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Abstract: We report here that spiral and curl antennas are essentially the same when using the moment method. This aids in the understanding and design of the two antennas, and serves as the groundwork for new ideas regarding antennas. First, the spiral antenna height above the ground plane was gradually reduced, and at each height, the spiral configuration parameters were optimized for an axial ratio of less than 0.1 dB. It was found that the spiral antenna had configuration parameters almost the same as those for a curl antenna at a height of 0.15 wavelengths. Next, the curl antenna was analyzed with a reduced height. The antenna, at a height of 0.10 wavelengths, showed a 3 dB axial ratio bandwidth of 3%, with a VSWR of less than two. The analysis results are verified with experimental results.

Keywords: spiral antenna; curl antenna; low-profile antenna; circularly polarized antenna

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1. Introduction

Circularly polarized (CP) elements, such as patch and cross slot antennas, have been found in many applications [1,2]. The patch and cross slot are resonant antennas, and usually require two feeds with the same amplitude and a phase difference of 90° for CP radiation. To incorporate the two feeds into one, we often use perturbation segments [3] and slots of slightly different lengths [4].

Spiral [5] and curl [6] antennas are also known as CP elements [7,8]. These are non-resonant antennas, and are excited with a single feed. This paper focuses on the spiral and curl antennas because of their simple feed systems.

Backing the spiral antenna with a ground plane is a simple method used to form a unidirectional radiation beam. The spiral antenna and ground plane spacing is conventionally chosen to be one-quarter wavelength [9,10]. This spacing (antenna height) has been reduced using several techniques: water dielectric [11] and magnetodielectric [12] substrates, and a ring-shaped absorber [13].

This paper aims to reduce spiral antenna height above the ground plane without any particular substrate or absorber. The spiral configuration parameters are appropriately selected so that the antenna radiates a CP wave. The change in radiation characteristics with decreasing antenna height (down to 0.15 wavelengths) are discussed using simulated results based on the moment method [14].

We also analyze a curl antenna above the ground plane, considering that the antenna is regarded as a simplified version of a single-arm spiral antenna. The analysis enables one to understand the relationship between the spiral and curl antennas. Furthermore, the analysis leads to the realization of a low-profile curl antenna (with a height of 0.10 wavelengths).

It is necessary to clarify the difference between the present paper and the authors' preliminary conference paper [15]. The preliminary paper shows only simulated CP wave bandwidths of non-resonant spiral and curl antennas to supplement resonant loop bandwidths. In contrast, the present paper further investigates the input impedance of the

spiral and curl antennas and impedance matching. An electromagnetic coupling feed is adopted to a resultant low-profile curl antenna, and the radiation characteristics, including the VSWR, radiation patterns, and gain, are presented alongside experimental work. This paper also demonstrates that adjacent arm distance and straight part length (d and L_f in Figure 1) are critical for reducing the antenna height, which was not discussed in the preliminary paper.

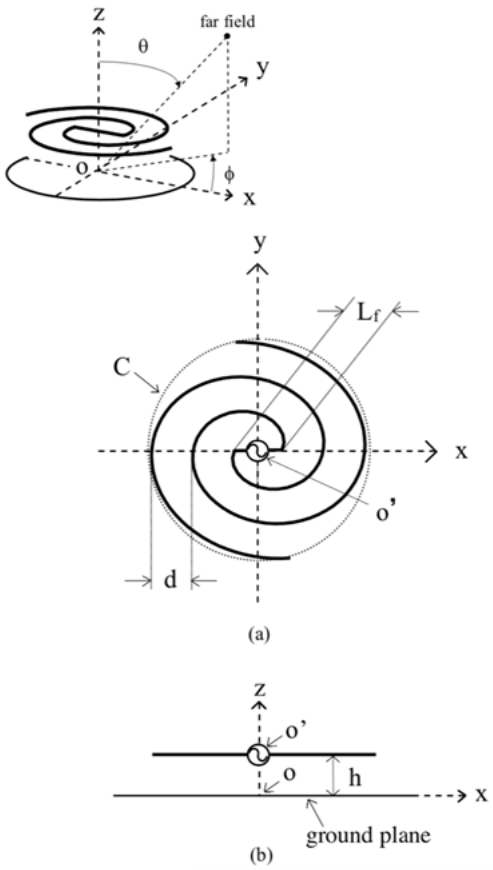


Figure 1. Two-arm spiral antenna: (**a**) perspective and top views; (**b**) side view.

To date, spiral and curl antennas have only been individually investigated, and the abovementioned preliminary study [15] is the only one to explore the relationship between the two antennas. This relationship is further examined in this paper, the results of which aid in understanding and designing spiral and curl antennas. In other words, the novelty of this paper is that it examines both spiral and curl antennas and notices essentially the same configurations of the two antennas, for the first time. Therefore, this paper serves as the groundwork for new ideas in antenna design, including spiral and curl antennas, in the future.

2. Spiral Antenna and Analysis Method

Figure 1 shows the configuration of a two-arm spiral antenna. The antenna is located at height h above the ground plane. The spiral arm is made of a wire of radius ρ and is defined by the Archimedean spiral function: $r = a_s \cdot \phi_s$, where r is the distance from the spiral center o' ($x = y = 0$, $z = h$) to a point on the arm, a_s is a spiral constant, and ϕ_s is a winding angle starting at ϕ_{st} and ending at ϕ_{end}. The spiral outer circumference and adjacent arm distance are designated as C ($=2\pi a_s \cdot \phi_{end}$) and d ($=\pi a_s$), respectively. The antenna is excited at the spiral center o', the center point of a straight part of length L_f ($=2\, a_s \cdot \phi_{st}$).

The ground plane is assumed to be infinite, and image theory is applied to the antenna analysis [16]. The current distributions along the antenna arms are determined using the moment method [14,16], where piecewise sinusoidal functions are used for both the expansion and weighting functions. Based on the obtained current distributions, the radiation characteristics are calculated.

The wire radius is taken to be $\rho = 0.006\lambda_0$ (λ_0: the free-space wavelength at a test frequency of f_0) [15]. The wire radius ρ is fixed throughout this paper. The other configuration parameters (C, d, L_f) are varied subject to the objectives of the analysis.

In the analysis, self-developed software is used, where the wire radius is assumed to be small compared with λ_0. This assumption ensures that the radiation characteristics can be calculated by only the current in the wire axis direction [17]. Note that image theory allows us to analyze the (real) antenna on the $+z$ side and the image antenna on the $-z$ side, removing the ground plane. Therefore, the antenna height reduction means that the real antenna approaches the image, resulting in stronger mutual coupling between the real and image antennas.

The right side of Figure 2, denoted as "spiral antenna", shows the optimized parameters (C, d, L_f) versus the antenna height h. The optimization is performed so that the antenna radiates a CP wave with an axial ratio of less than 0.1 dB (Section 3 will explain the left side of Figure 2, denoted as "curl antenna"). It is found that the adjacent arm distance d monotonously decreases, and the circumference C converges to $1\lambda_0$ with a decrease in the antenna height h. The optimized parameters, for example, are C, d, $L_f = 1.18\lambda_0$, $0.02\lambda_0$, $0.20\lambda_0$, respectively, at $h = 0.15\lambda_0$. Note that the antenna of $h < 0.25\lambda_0$ cannot radiate a CP wave without the straight part of proper length L_f.

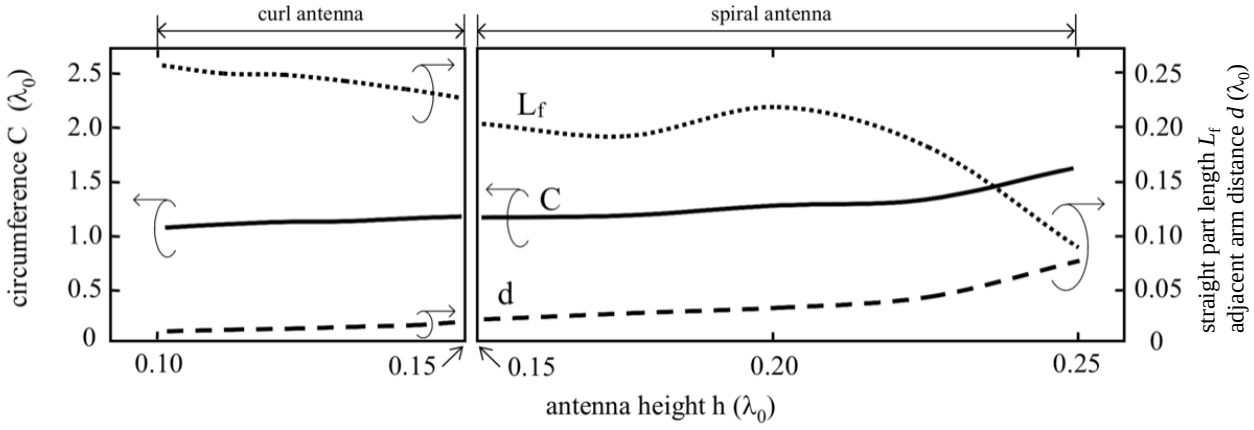


Figure 2. Configuration parameters optimized for CP radiation versus antenna height h.

The frequency bandwidth for a 3 dB axial ratio criterion against the antenna height h is presented on the right side of Figure 3. The optimized parameters (C, d, L_f) on the right side of Figure 2 are used. The axial ratio bandwidth decreases as the antenna height is reduced. A bandwidth of 24% at $h = 0.25\lambda_0$ decreases to 8% at $h = 0.15\lambda_0$.

The right side of Figure 4 shows the input impedance $Z_{in} = R_{in} + j\,X_{in}$ versus h. It is observed that the input impedance is almost purely resistive, even when the antenna height h is reduced. The resistance R_{in} becomes higher as h decreases.

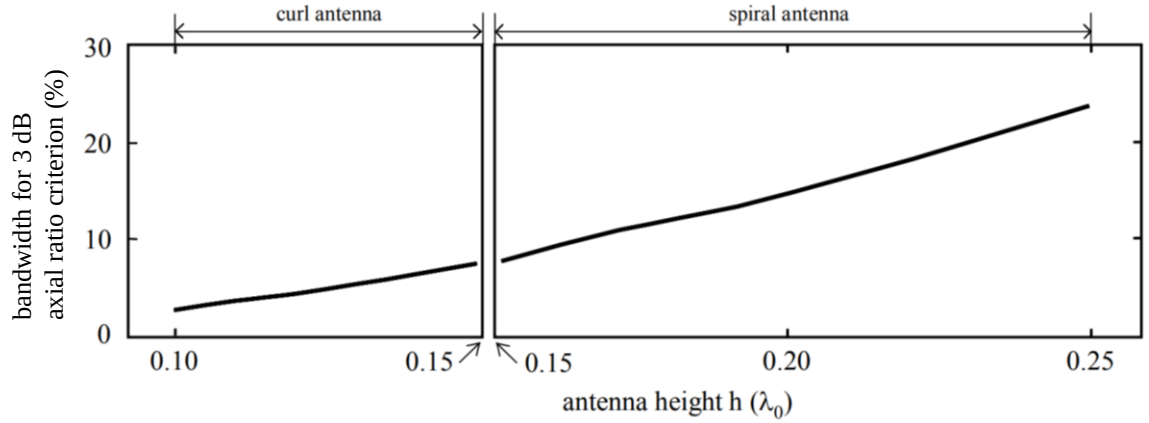


Figure 3. CP wave bandwidth versus antenna height *h*.

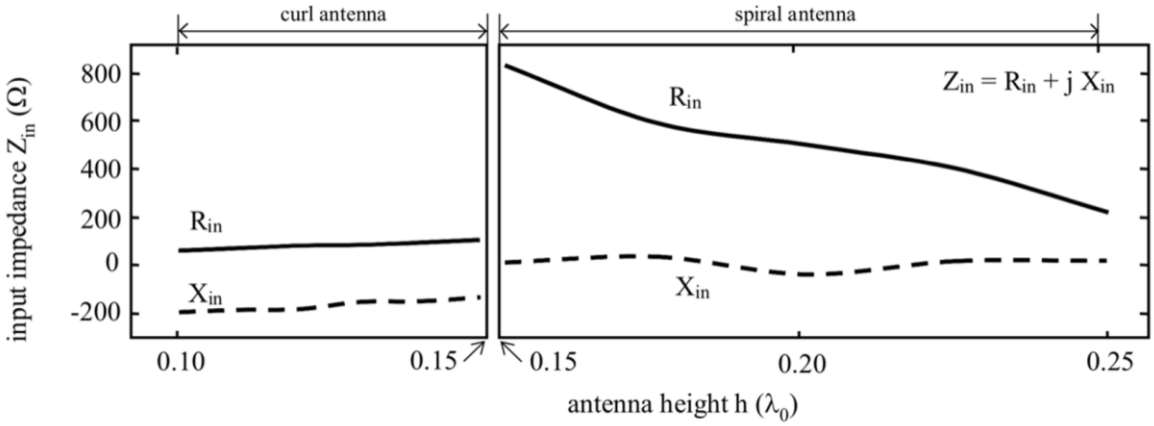


Figure 4. Input impedance versus antenna height *h*.

3. Curl Antenna

So far, we have obtained low-profile spiral antennas with $h < 0.25\lambda_0$ by optimizing the configuration parameters for CP radiation. This section realizes a low-profile curl antenna, as for the spiral antenna. Two types of feed systems are considered for the input impedance characteristics.

3.1. Direct Feed

Figure 5 shows the configuration of a curl antenna. The antenna is made of a wire of radius ρ, which is bent at height *h* and curled above the ground plane. The antenna consists of vertical (*o*-*o*′), horizontal (*o*′-*a*), and curled (*a*-*b*) parts. The Archimedean spiral function defines the curled part, with its center being at point *o*′. The length of the horizontal part (*o*′-*a*) is given by $a_s \cdot \phi_{st} = L_f/2$. The curl's outer circumference and adjacent arm distance are given by $2\pi a_s \cdot \phi_{end} = C$ and $2\pi a_s = 2\,d$, respectively. Note that the definitions (C, d, L_f) used for the two-arm spiral antenna shown in Figure 1 apply to the present curl antenna. The antenna is fed by a coaxial line at the lower end of the vertical wire, at point *o*.

Preliminary calculations show that, when the configuration parameters are C, d, $L_f = 1.19\lambda_0$, $0.02\lambda_0$, $0.22\lambda_0$, respectively, a curl antenna at $h = 0.15\lambda_0$ radiates a CP wave with an axial ratio of less than 0.1 dB. These parameters are found to be almost the same as those for a low-profile spiral antenna at $h = 0.15\lambda_0$, as described in Section 2: C, d, $L_f = 1.18\lambda_0$, $0.02\lambda_0$, $0.20\lambda_0$, respectively. From the similarity in the configuration parameters for CP radiation, it can be said that the curl antenna corresponds to a low-profile spiral antenna.

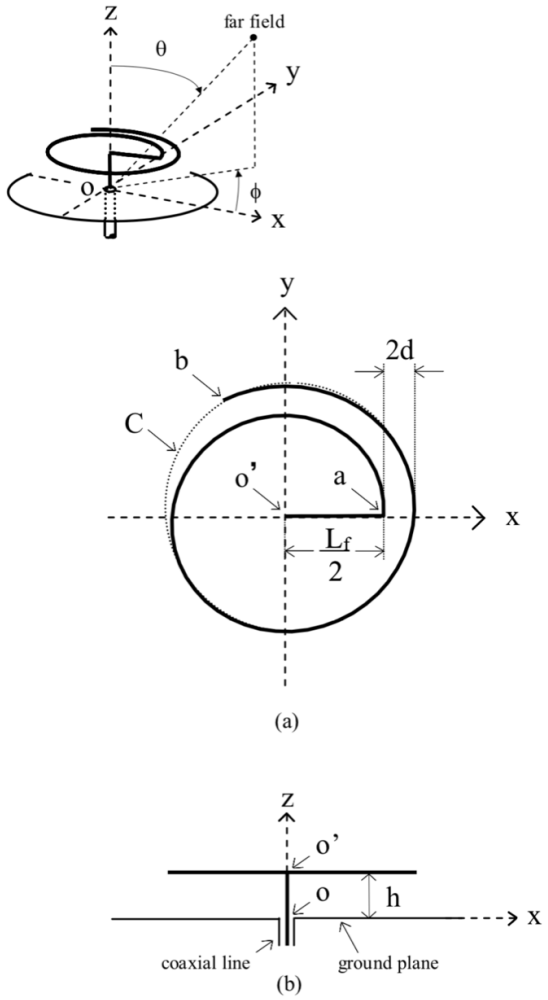


Figure 5. Curl antenna with a direct feed: (**a**) perspective and top views; (**b**) side view.

Now, we reduce the antenna height of the curl from $h = 0.15\lambda_0$. The left side of Figure 2, denoted as "curl antenna", shows the optimized parameters (C, d, L_f) for CP radiation with an axial ratio criterion of 0.1 dB. It is emphasized that the outer circumference C and the adjacent wires at distance d smoothly vary in the antenna height range of the curl and the spiral.

The left part of Figure 3 shows the 3 dB axial ratio bandwidth versus height h. A bandwidth of 8% at $h = 0.15\lambda_0$ decreases to 3% at $h = 0.10\lambda_0$. It should be noted that the curl antenna with $h = 0.10\lambda_0$ can be constructed, but the previous two-arm spiral antenna with $h = 0.10\lambda_0$ cannot be constructed due to the extremely small adjacent wires at distance d. The curl, therefore, has an advantage over the spiral with respect to reducing antenna height.

The left part of Figure 4 depicts the input impedance $Z_{in} = R_{in} + j\,X_{in}$ for a smaller antenna height than $h = 0.15\lambda_0$. The curl has an input impedance of $80 - j\,200\ \Omega$ at $h = 0.10\lambda_0$, which gives a high VSWR (of 12 to a 50-Ω coaxial line). In Section 3.2, impedance matching is considered.

3.2. Electromagnetic Coupling Feed

Impedance matching is performed with an electromagnetic coupling feed system. Figure 6 shows a curl antenna electromagnetically coupled to an inverted L-wire of radius ρ. The vertical and horizontal lengths of the L-wire are designated as L_V and L_H, respectively. The lower end of the vertical part, point o, is excited by a coaxial line. The horizontal part of the L-wire is just under the horizontal part (o'-a) of the curl antenna, without physical contact.

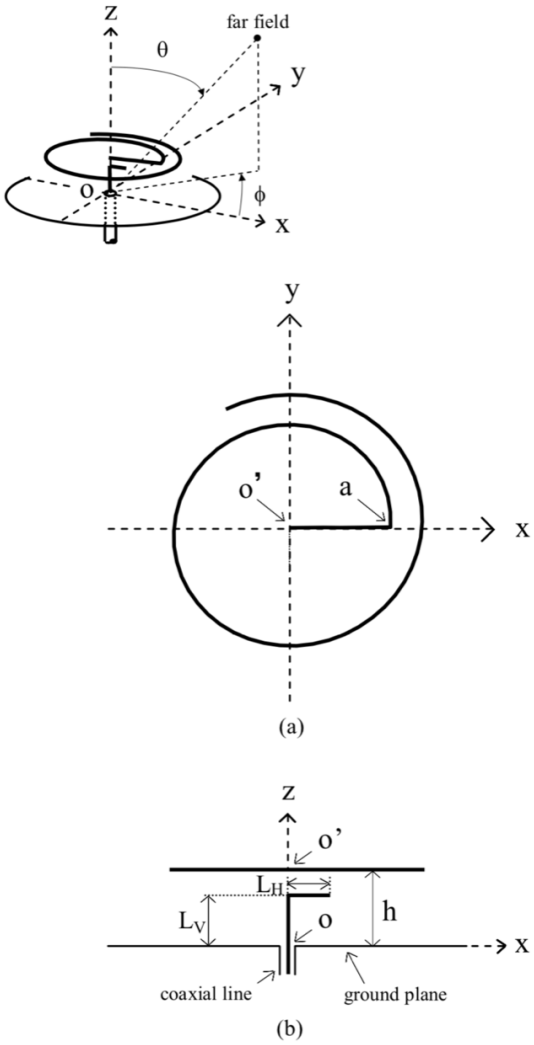


Figure 6. Curl antenna with an electromagnetic coupling feed: (**a**) perspective and top views; (**b**) side view.

We realize impedance matching for a low-profile curl antenna, holding the antenna height at $h = 0.10\lambda_0$ with C, d, $L_f = 1.09\lambda_0$, $0.007\lambda_0$, $0.25\lambda_0$, respectively, revealed in Figure 2. The lengths (L_V, L_H) are optimized at a test frequency f_0 so that the VSWR is as small as possible. The VSWR relative to a 50-Ω coaxial line is evaluated to be 1.7 for, respectively, L_V, $L_H = 0.067\lambda_0$, $0.134\lambda_0$.

So far, we have revealed the input impedance at a test frequency of f_0. We next investigate the frequency responses of the antenna characteristics.

The solid line in Figure 7a shows the VSWR relative to a 50-Ω coaxial line. The VSWR for the curl with the direct feed, discussed in Section 3.1, is also presented with a dotted line. The VSWR for the electromagnetic coupling feed shows a remarkable improvement. The experimental results confirm this. For the experiment, we fabricate an antenna at $f_0 = 3$ GHz using a large conducting plane of $10\lambda_0 \times 10\lambda_0$ to approximate the theoretical ground plane of an infinite extent. The prototype's photographs are shown in Figure 8. The VSWR is measured using a vector network analyzer (Anritsu MS46322A, Advanced Test Equipment Corporation, San Diego, CA, USA).

The solid lines in Figure 7b show the frequency responses of the axial ratio and gain. The axial ratios are less than 3 dB in a frequency range of $0.980f_0$ to $1.007f_0$ (3% CP wave bandwidth), within which the gain is almost constant (9 dBi). This CP wave bandwidth is the same as that for the direct feed (see the dotted line for the direct feed). The experimental results are also presented in this figure. Good agreement is seen to exist between the

theoretical and experimental results. The axial ratio and gain are measured in an anechoic chamber using broadband (Q-par Angus) and standard gain horn (Narda 644) antennas. We use the vector network analyzer as a transmitter and receiver to determine the radiation phase for evaluating the axial ratio. Note that the antenna does not have a conventional lossy dielectric substrate. Therefore, the radiation efficiency is almost 100% (up to 12 GHz with negligible conductor losses [18]).

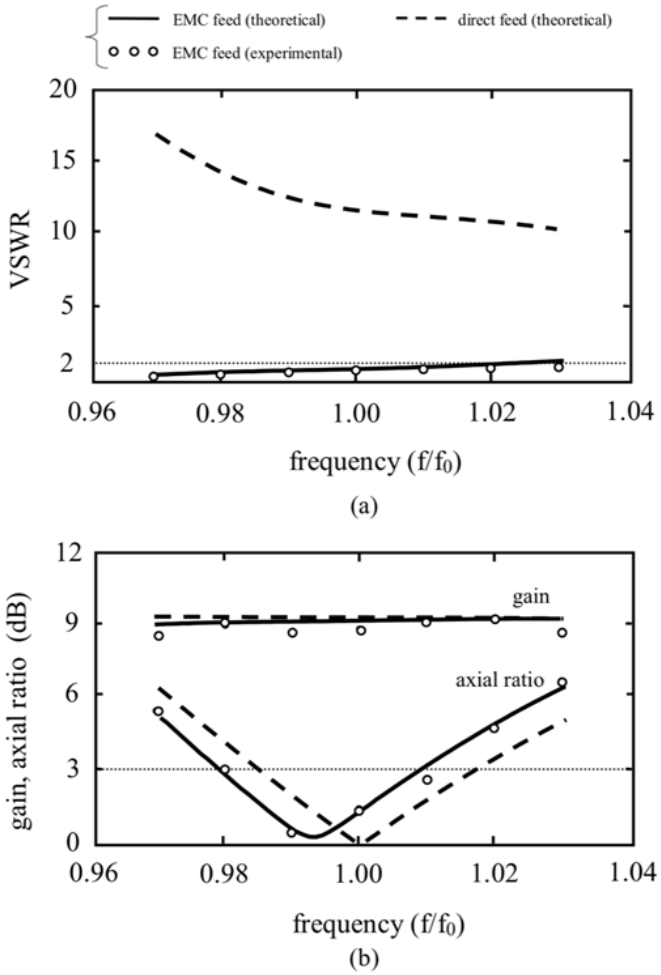
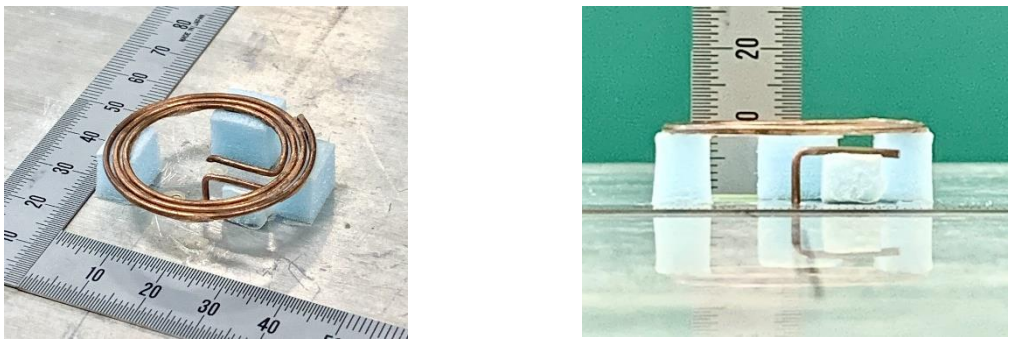


Figure 7. Frequency responses of a curl antenna: (**a**) VSWR; (**b**) axial ratio and gain.



(**a**) (**b**)

Figure 8. Photographs of a prototype: (**a**) perspective view; (**b**) side view.

Figure 9 shows the radiation patterns when the axial ratio becomes minimal at $f = 0.993 f_0$. The radiation field is decomposed into right- and left-handed CP waves with

E_R and E_L intensities. It is found that a broad CP beam is radiated in the direction normal to the antenna plane. The half-power beamwidths are 71° and 70° in the ϕ = 0° and 90° planes, respectively. The axial ratios in the half-power beamwidths are less than 2.5 dB. This figure also shows the experimental results, which agree with the theoretical results. The radiation patterns are measured in the anechoic chamber using the broadband horn antenna at a distance of 3 m from the fabricated antenna. The fabricated antenna is rotated on a turntable, while the horn antenna is fixed.

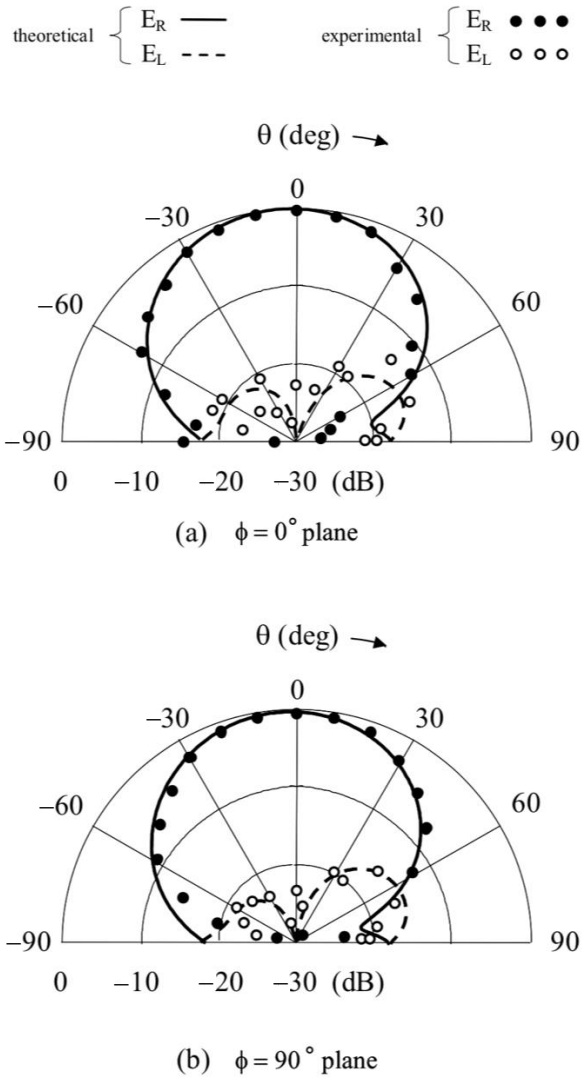


Figure 9. Radiation patterns of a curl antenna at $f = 0.993 f_0$.

Finally, we summarize the differences between the curl and spiral antennas. The differences are summarized in Table 1. It is emphasized that the curl has an antenna part vertical to the ground plane (the part *o*-*o*′ in Figure 5). In contrast, the spiral antenna does not have a vertical part.

Table 1. Differences between curl and spiral antennas.

Antenna	Number of Arms	Antenna Part Vertical to the Ground Plane	Antenna Height Range (λ_0)	3 dB Axial Ratio Bandwidth in Its Height Range (%)	Input Impedance ($Z_{in} = R_{in} + j X_{in}$) in Its Height Range
curl	1	present	0.10–0.15	3–8	$\lvert X_{in} \rvert > R_{in}$
spiral	2	absent	0.15–0.25	8–24	$X_{in} \approx 0$

4. Conclusions

We studied spiral and curl antennas at an antenna height h above the ground plane. First, a two-arm spiral antenna was analyzed using the moment method. It was found that the antenna at $h < 0.25\lambda_0$ radiates a CP wave with the help of the straight part of proper length. The spiral configuration parameters at $h = 0.15\lambda_0$ were found to be close to those of the curl antenna at the same height. Subsequently, a curl antenna was analyzed at $h < 0.15\lambda_0$. It was found that the configuration parameters optimized for CP radiation vary smoothly over the entire height range of the curl and spiral antennas, implying that the two antennas are essentially the same. It is emphasized that the curl antenna at $h = 0.10\lambda_0$ can be fabricated, but the spiral at the same height cannot be due to a minimal distance required between adjacent arms.

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References

1. Volakis, J.L. (Ed.) *Antenna Engineering Handbook*, 4th ed.; MacGraw-Hill: New York, NY, USA, 2007.
2. James, J.R.; Hall, P.S. (Eds.) *Handbook of Microstrip Antennas*; Peregrinus: Stevenage, UK, 1989.
3. Ramirez, R.R.; Faviis, F.D. A mutual coupling study of linear and circular polarized microstrip antennas for diversity wireless systems. *IEEE Trans. Antennas Propag.* **2003**, *51*, 238–248. [CrossRef]
4. Sievenpiper, D.; Hsu, H.-P.; Riley, R.M. Low-profile cavity-backed crossed-slot antenna with a single-probe feed designed for 2.34-GHz Satellite radio applications. *IEEE Trans. Antennas Propag.* **2004**, *52*, 873–879. [CrossRef]
5. Kaiser, J.A. The Archimedean two-wire spiral antenna. *IRE Trans. Antennas Propag.* **1960**, *8*, 312–323. [CrossRef]
6. Nakano, H.; Okuzawa, S.; Ohishi, K.; Mimaki, H.; Yamauchi, J. A curl antenna. *IEEE Trans. Antennas Propag.* **1993**, *41*, 1570–1575. [CrossRef]
7. Shi, Y.; Wu, Q.W.; Ming, J. An Archimedean spiral antenna for generation of tunable angular momentum wave. *IEEE Access* **2021**, *9*, 63122–63130. [CrossRef]
8. Hirose, K.; Ito, N.; Nakano, H. A dual-curl antenna with coplanar feedline for sequential rotation. *Electron. Lett.* 2022, *in press*. [CrossRef]
9. Wu, S.-C. Analysis and design of conductor-backed square Archimedean spiral antennas. *Electromagnetics* **1994**, *14*, 305–318. [CrossRef]
10. Nakano, H.; Okabe, Y.; Mimaki, H.; Yamauchi, J. A monofilar spiral antenna excited through a helical wire. *IEEE Trans. Antennas Propag.* **2003**, *51*, 661–664. [CrossRef]
11. Hu, Z.; Wang, S.; Shen, Z.; Wu, W. Broadband polarization-reconfigurable water spiral antenna of low profile. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 1377–1380. [CrossRef]
12. Tanabe, M.; Masuda, Y.; Nakano, H. Low-profile spiral antenna placed on an extremely thin magnetodielectric substrate. *IEEE Antennas Wirel. Propag. Lett.* **2017**, *16*, 2050–2053. [CrossRef]
13. Shih, T.; Behdad, N. A compact, broadband spiral antenna with unidirectional circularly polarized radiation patterns. *IEEE Trans. Antennas Propag.* **2015**, *63*, 2776–2781. [CrossRef]
14. Harrington, R.F. *Fields Computation by Moment Methods*; Macmillan: New York, NY, USA, 1968.
15. Hirose, K.; Obuse, K.; Uchikawa, Y.; Nakano, H. Low-profile circularly polarized radiation elements—Loops with balanced and unbalanced feeds. In Proceedings of the IEEE Antennas and Propagation Society International Symposium, San Diego, CA, USA, 5–11 July 2008; pp. 1–4.
16. Hirose, K.; Nakamura, K.; Nakano, H. Bent and branched microstrip-line antennas for circular polarization. *Appl. Sci.* **2022**, *12*, 1711. [CrossRef]

17. Nakano, H.; Yamashita, E. (Eds.) *Fields Analysis Methods for Electromagnetic Wave Problems—Volume 2*; Artech House: Norwood, MA, USA, 1996.
18. Nakano, H.; Oka, T.; Hirose, K.; Yamauchi, J. Analysis and measurements for improved crank-line antennas. *IEEE Trans. Antennas Propag.* **1997**, *45*, 1166–1172. [CrossRef]