Progress In Electromagnetics Research Letters, Vol. 108, 1–8, 2023

Coplanar Series-Fed Spiral Antenna Arrays for Enlarged Axial Ratio Bandwidth

Kazuhide Hirose[1, *], Yuki Tamura[1], Masaki Tsugane[1], and Hisamatsu Nakano[2]

Abstract—We study two array antennas to expand a 3 dB axial ratio bandwidth. Each array is located at a quarter wavelength above the ground plane and analyzed using the moment method. First, we use paired spiral elements fed by balanced parallel lines to avoid unwanted radiation from the feedline. It is found that the antenna shows an axial ratio bandwidth of 30%. Next, the elements are separated and fed by a single feedline to simplify the feed system. It is revealed that the antenna can radiate a circularly polarized wave under a feedline radiation of less than -16 dB. The frequency responses show that an axial ratio < 3 dB and VSWR < 2 are obtained in a bandwidth of 21%, where the gain is more than 13.3 dBi. The simulated results are verified with experimental ones.

1. INTRODUCTION

Circularly polarized (CP) beam formation has been investigated using an array antenna with a coplanar series feed above the ground plane [1–6]. The antenna has the advantage of a simple feed system compared with a multilayer corporate feed. The investigation so far has been restricted to a resonant element array, such as a patch [1–4] or loop [5, 6] element.

This letter presents a non-resonant element array for an enlarged CP wave bandwidth. Non-resonant spiral elements are arrayed above the ground plane and excited in series by a coplanar feed line. The antenna characteristics are discussed using simulated results based on the moment method [7].

This letter studies two spiral element arrays, showing a wider CP wave bandwidth than conventional resonant element arrays. One array is excited using balanced parallel feedlines, and the other is excited using a single feedline. To the best of the authors' knowledge, it is the first time to study a series-fed spiral element array with a coplanar feedline above the ground plane.

To date, resonant and non-resonant radiation elements have been systematically studied for CP radiation [8]. The studies have shown that as the element height above the ground plane increases, the difference between the CP wave bandwidths of the resonant and non-resonant elements becomes appreciable. To emphasize a wider CP wave bandwidth of the non-resonant element, we take the present spiral height to be a quarter wavelength.

This letter first shows the need to reduce the coplanar feedline radiation that deteriorates CP radiation from a paired spiral element. Next, we design a paired spiral element array fed by balanced parallel lines to avoid feedline radiation. Last, the elements are separated and fed by a single feedline for a simple feed system. The radiation characteristics are compared with those of the balanced feedlines. The simulated results are validated with experimental work.

Received 9 October 2022, Accepted 9 November 2022, Scheduled 20 November 2022

* Corresponding author: Kazuhide Hirose (khirose@shibaura-it.ac.jp).

[1] College of Engineering, Shibaura Institute of Technology, Tokyo 135-8548, Japan. [2] Science and Engineering, Hosei University, Tokyo 184-8584, Japan.

2. PAIRED SPIRAL ELEMENT ARRAY

Figure 1 shows an antenna configuration and a coordinate system. Single arm spirals are paired in the y-direction with spacing S_y and arrayed in the x-direction with spacing S_x. Each spiral is located at a height h above the ground plane and specified by circumference C, adjacent arms at distance d, and straight length L_s, as shown in Figure 1(a).

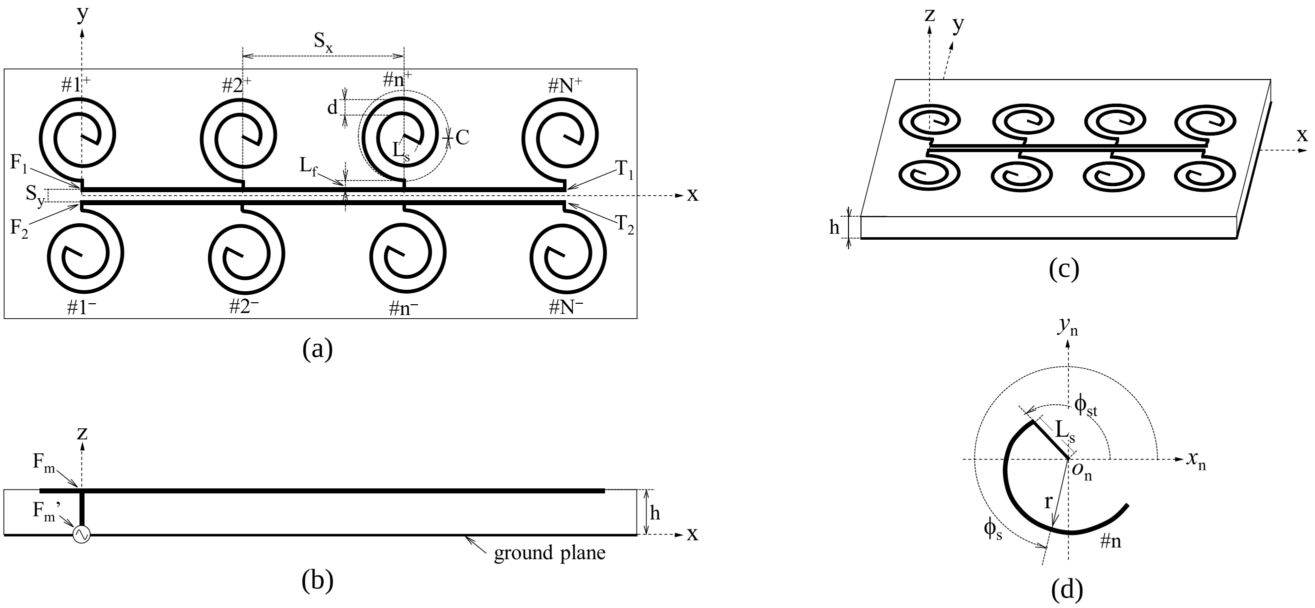


Figure 1. Paired spiral element array with balanced parallel feedlines F_m-T_m ($m = 1$ and 2). (a) Top view. (b) Side view. (c) Perspective view. (d) The Archimedean function defines a spiral arm: $r = a_s\phi_s$, where r is the radial distance from origin o_n to a point on the arm, a_s is a spiral constant, and ϕ_s is a winding angle ranging $\phi_{st} \le \phi_s \le \phi_{end}$. The spiral arm is specified by circumference $C = 2\pi r_{\max}$ with $r_{\max} = a_s\phi_{end}$, adjacent arms at distance $d = 2\pi a_s$, and straight length $L_s = r_{\min} = a_s\phi_{st}$.

N paired-spiral elements are connected to coplanar parallel feedlines F_m-T_m ($m = 1$ and 2) via segments of length L_f. The left ends F_m are excited with two sources having the same amplitudes and a phase difference of 180° through vertical straight-lines F_m-F_m' shown in Figure 1(b). The right ends T_m of the feedlines are connected to an element of $\#N^{\pm}$. The antenna is made of wires with a radius ρ [5, 6, 9]. Note that the spirals on the $+y$ side are rotated by 180° with respect to the ones on the $-y$ side, compensating for an excitation phase difference of 180°.

The antenna is analyzed using the moment method [7]. The ground plane size is assumed to be infinite, and image theory is used. The spacing between the paired spirals is set to be $S_x = 1\lambda_0$ for broadside beam formation, where λ_0 is the free-space wavelength at a test frequency f_0. The spiral parameters (C, d, L_s) and segment length L_f are selected for CP radiation. The other configuration parameters are fixed throughout this letter to facilitate comparison: $h = \lambda_0/4$ [5, 8], $(N, S_y, \rho) = (4, \lambda_0/40, \lambda_0/200)$ [5].

A wire antenna analysis in this letter implies a strip antenna one since a wire of radius ρ is regarded as a strip of equivalent width $w = 4\rho$ [10]. We locate the strip antenna on an air dielectric substrate (DS) to avoid decreased radiation efficiency [9]. Based on an air DS antenna, we may design a conventional DS antenna by changing the configuration parameters in terms of λ_0 to those in terms of λ_g [9, 11], where λ_g is a guided wavelength on a conventional DS.

Preliminary calculations show that reducing unwanted radiation from the segments of length L_f is necessary for CP radiation. This is shown in Figure 2, where the axial ratio is evaluated versus L_f for $N = 1$, without the parallel feedlines F_m-T_m. It is observed that as L_f increases to $0.25\lambda_0$ [5], the axial ratio deteriorates to be more than 3 dB, unlike the case of resonant radiation elements. From this result, the segment length is chosen to be small ($L_f = 0.05\lambda_0$) and fixed throughout this letter.

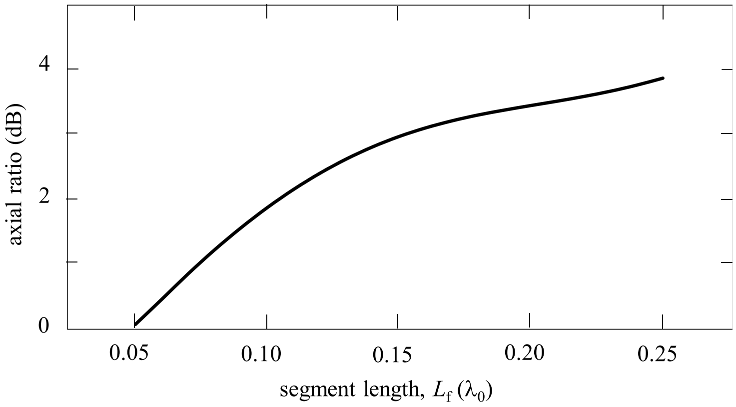


Figure 2. Simulated axial ratio versus segment length L_f for $N = 1$ and $(C, d, L_s) = (1.54\lambda_0, 0.064\lambda_0, 0.08\lambda_0)$.

Figure 3 shows the simulated radiation pattern when the configuration parameters are $(C, d, L_s) = (1.50\lambda_0, 0.056\lambda_0, 0.10\lambda_0)$ and $S_x = 1.00\lambda_0$. The radiation is shown with right (E_R) and left-hand (E_L) CP wave components. It is found that the antenna radiates a CP beam normal to the antenna plane in the $+z$-axis direction. The half-power beamwidth (HPBW) is 13°, and the gain is 16.7 dBi.

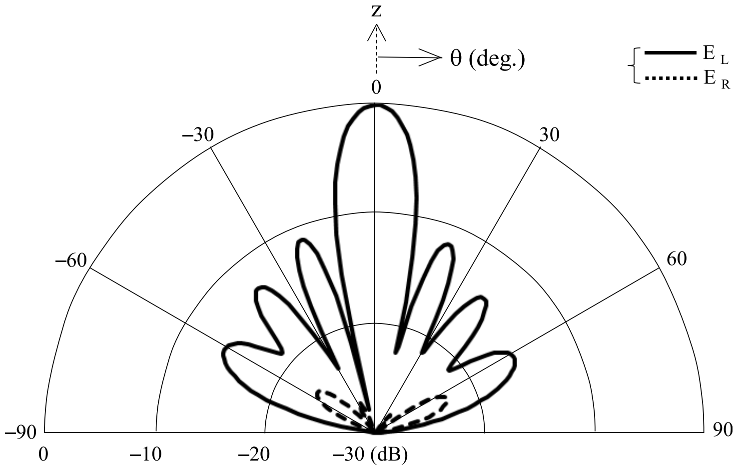


Figure 3. Simulated radiation pattern of a paired spiral element array.

3. SEPARATED SPIRAL ELEMENT ARRAY

The antenna in Section 2 requires two sources for parallel feedlines. This section studies another antenna with one source for a simple feed system.

The antenna configuration is shown in Figure 4. The antenna is created using Section 2's (see Figure 1) as follows:

(1) The feedline F_2-T_2 and vertical straight-line F_2-F_2' are removed, and the spirals of $\#n^-$ on the $-y$ side are connected to the feedline F_1-T_1 via segments of length L_f.

(2) The spirals of $\#n^-$ with their segments are shifted along the feedline F_1-T_1 toward the right end T_1 by $S_x/2$. This shift makes an excitation phase difference of 180° between the spirals on the $\pm y$ sides as the balanced feedlines in Section 2. Note that we remove the rightmost spiral of $\#N^-$ on the $-y$ side to keep the feedline length unchanged.

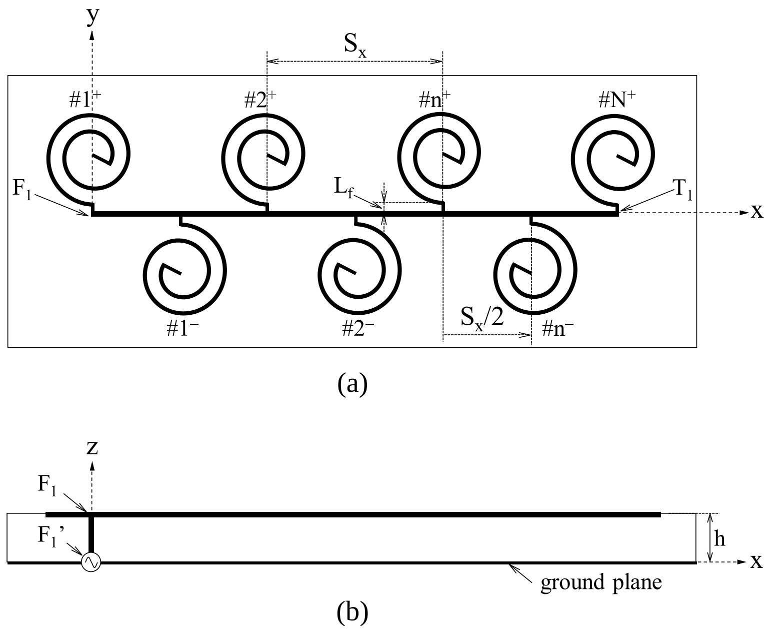


Figure 4. Separated spiral element array with a single feedline F_1-T_1. (a) Top view. (b) Side view.

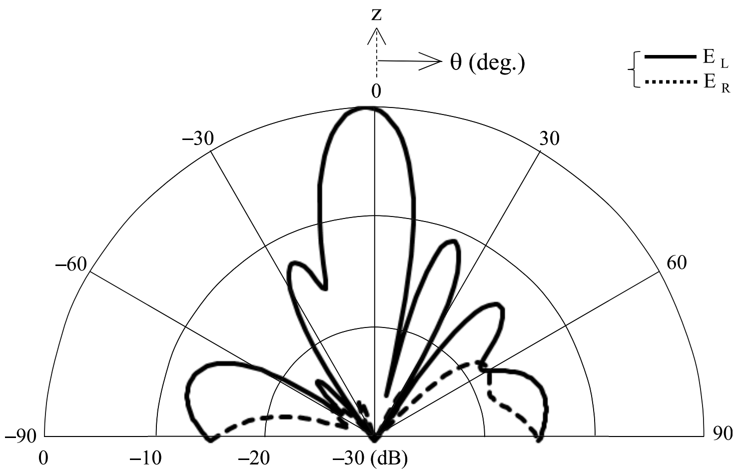
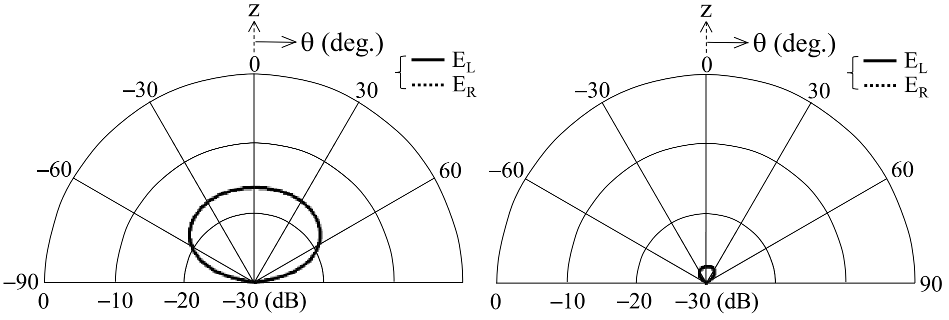


Figure 5. Simulated radiation pattern of a separated spiral element array.

The antenna is designed to radiate a broadside beam. The simulated radiation pattern is shown in Figure 5. The configuration parameters are $(C, d, L_s) = (1.32\lambda_0, 0.056\lambda_0, 0.11\lambda_0)$ with $S_x = 1.00\lambda_0$. It is found that a CP beam can be formed in the $+z$ axis direction even for a single coplanar feed line. The HPBW is 14°, and the gain is 14.2 dBi.

A question arises when we recall the deterioration in an axial ratio versus L_f shown in Figure 2. How can the present antenna radiate a CP wave even for a single feedline F_1-T_1? The feedline length reaches $3S_x(= 3\lambda_0)$, much longer than L_f's segment length. To explain the reason, we evaluate the partial radiation from the feedline F_1-T_1. In other words, we extract feedline radiation from the total radiation shown in Figure 5.

Figure 6(a) shows partial radiation from the single feedline F_1-T_1. It is revealed that unwanted radiation from the single feedline is less than -16 dB, which is normalized using the value of the maximum radiation from the total antenna (see Figure 5). For comparison, partial radiation from the balanced parallel feedlines F_m-T_m in Section 2 is shown in Figure 6(b). Unwanted radiation from the balanced feedlines is negligible as expected, less than -28 dB, normalized using the maximum radiation



(a) (b)

Figure 6. Partial radiation from the feedline of a spiral element array. (a) Single feedline F_1-T_1 of a separated spiral element array. (b) Balanced parallel feedlines F_m-T_m of a paired spiral element array. Note that the dotted line does not appear since it overlaps with the solid line.

value (see Figure 3). It can be said that the present antenna can radiate a CP wave under unwanted radiation of less than −16 dB from the single feedline, which is tolerable for broadside beam formation.

Solid lines in Figure 7 show the simulated frequency responses of the present antenna. It is found that the axial ratio is less than 3 dB in a frequency range of $0.95f_0$ to $1.18f_0$, corresponding to a bandwidth of 22%. In the bandwidth, the gain is more than 13.5 dBi. For comparison, the dotted lines show those of the paired spiral element array in Section 2. The bandwidth is 30%, with a gain of more than 15.0 dBi.

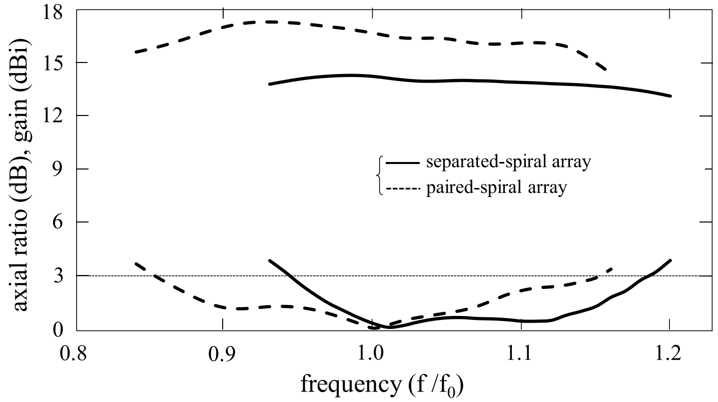


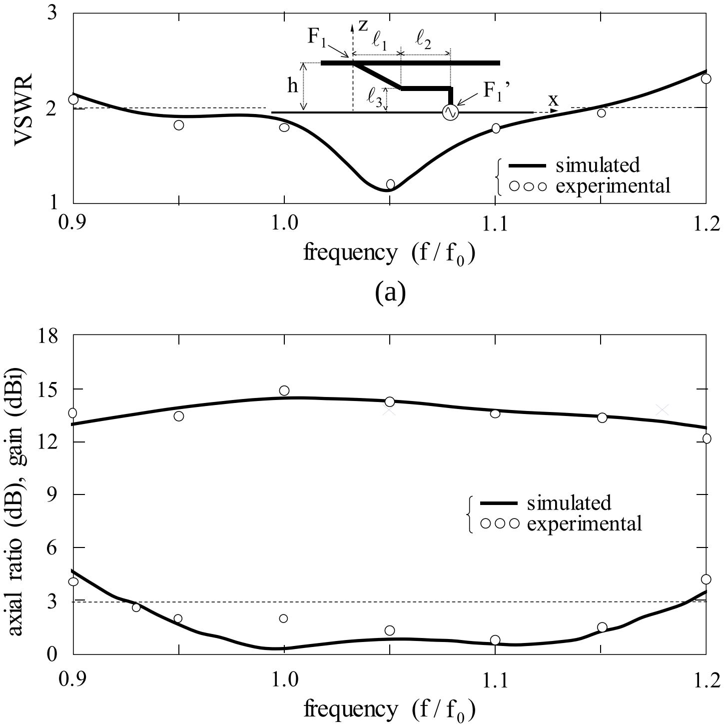
Figure 7. Simulated frequency responses of axial ratio and gain in the beam direction for separated and paired spiral element arrays.

4. EXPERIMENTAL WORK

The antenna in Section 3 has a vertical straight-line F_1-F_1' shown in Figure 4. This section transforms the straight line into a tapered one for impedance matching.

The inset of Figure 8(a) shows a vertical tapered-line F_1-F_1', specified by the parameters of (ℓ_1, ℓ_2, ℓ_3). The parameters are selected so as not to deteriorate the radiation characteristics for the vertical straight-line. Note that the other configuration parameters are the same as those in Section 3.

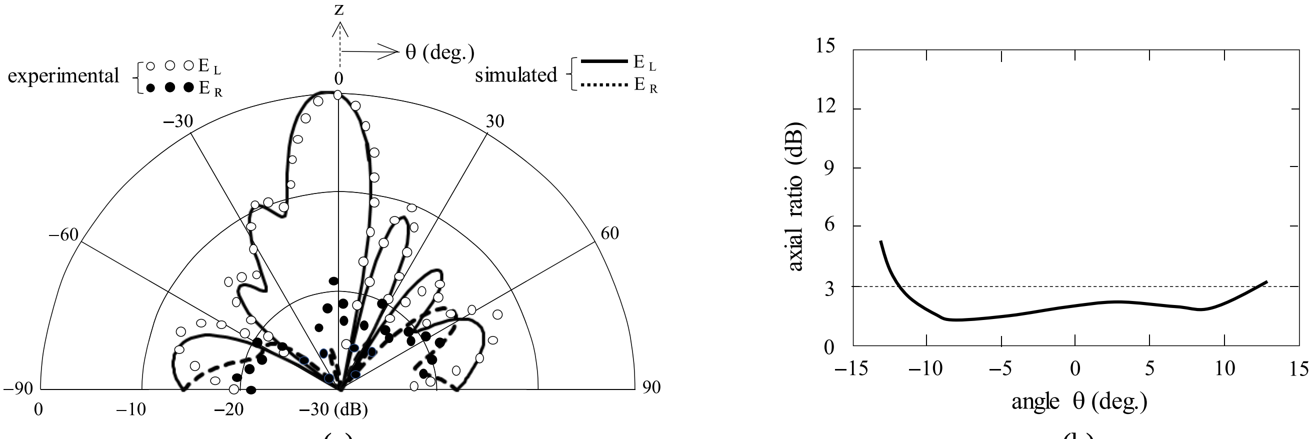
The simulated VSWR versus frequency is shown with a solid line in Figure 8(a), together with the gain and axial ratio. The tapered line parameters are $(\ell_1, \ell_2, \ell_3) = (0.21\lambda_0, 0.18\lambda_0, 0.04\lambda_0)$. It is found that a VSWR < 2 and axial ratio < 3 dB are obtained in a frequency range of $0.93f_0$ to $1.15f_0$ (21%), where the gain is more than 13.3 dBi. The solid and dotted lines in Figure 9(a) show a simulated radiation pattern, which is almost the same for the vertical straight-line (see Figure 5). The HPBW is 15°, and the gain is 14.5 dBi.



(a)

(b)

Figure 8. Frequency response of a separated spiral element array with a vertical tapered-line F_1-F_1'. (a) VSWR. (b) Axial ratio and gain in the beam direction.



(a)

(b)

Figure 9. Radiation pattern and axial ratio of a separated spiral element array with a vertical tapered-line F_1-F_1'. (a) Radiation pattern. (b) Axial ratio versus angle θ in the main beam.

So far, the radiation characteristics are discussed using simulated results. To verify the results, we perform experiments using an antenna fabricated at $f_0 = 3\,\mathrm{GHz}$ with a ground plane of $3\lambda_0 \times 9\lambda_0$. The small circles and dots in Figures 8 and 9(a) show the experimental results. They agree well with the simulated results shown with solid and dotted lines. As additional information, Figure 9(b) shows the experimental results of the axial ratio versus angle θ in the main beam shown in Figure 9(a). The axial ratio is less than 3 dB in an angle range of $-12° < \theta < 13°$.

Finally, our results are compared with those of other antenna arrays with a coplanar series feed above the ground plane. The comparisons are summarized in Table 1. It is emphasized that we enlarge

Table 1. Comparison with other antenna arrays with coplanar series feed above the ground plane.

Array element		**Array type**	**3 dB axial ratio bandwidth (%)**	**Gain (dBi)**	**Operating frequency (GHz)**	**Matched termination**
Patch	[1]	1×24	4	17.0	86	Required
	[2]	1×4	11.3	12.0	5	Required
		1×6	10.5	13.6	8	Required
	[3]	1×4	0.4	9.8	2	Not required
	[4]	1×7	10	12.3	10	Required
	[12]	$(1 \times 8) \times 15$	4	17.7	24	Required
	[13]	$(1 \times 13) \times 4$	7.1	21.6	12.0	Required
		$(1 \times 17) \times 4$	5.0	22.9	14.0	Required
Loop	[5]	2×4	18.9	15.8	3	Not required
	[6]	2×2	7.9	12.1	3	Not required
Present spiral		2×4	30	16.7	3	Not required
		1×7	21	14.5	3	Not required

a CP wave bandwidth by adopting a non-resonant spiral element for the first time.

Before conclusion, it is necessary to describe the radiation characteristics of a single spiral element above the ground plane of an infinite extent (see the inset of Figure 10). The spiral arm end is connected to a vertical wire of length $h\,(= \lambda_0/4)$, whose bottom end is excited using a coaxial line. The spiral parameters (C, d, L_s) are selected for CP radiation. Calculations show that the element of $(C, d, L_s) = (1.22\lambda_0, 0.046\lambda_0, 0.11\lambda_0)$ radiates a CP wave with an axial ratio of less than 3 dB in a frequency range of $0.94f_0$ to $1.20f_0$ (24%). Figure 10 shows the frequency response of the input impedance $Z_{in} = R_{in} + jX_{in}$ for $(C, d, L_s) = (1.22\lambda_0, 0.046\lambda_0, 0.11\lambda_0)$. It is observed that the input impedance is approximately $140 - j70\,\Omega$ in the CP wave bandwidth.

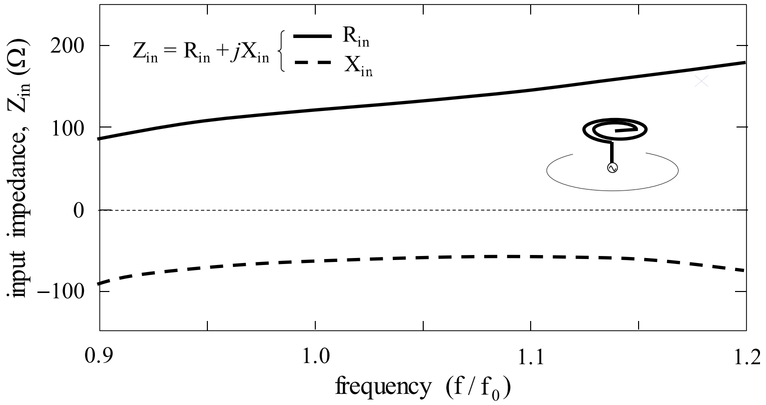


Figure 10. Simulated input impedance versus frequency for a spiral element.

5. CONCLUSION

We have investigated two types of non-resonant element arrays to enlarge an axial ratio bandwidth. Paired and separated spirals at $\lambda_0/4$ above the ground plane are arrayed and fed in series by coplanar parallel and single feedlines, respectively. Investigation reveals that length L_f of the segment connecting the spiral and feedline must be small ($L_f = 0.05\lambda_0$) for CP radiation, which is entirely different from that ($L_f = 0.25\lambda_0$) in a resonant element array. It is found that the paired and separated spiral element arrays show 3 dB axial ratio bandwidths of 30% and 22% with a feedline radiation of less than −28 dB and −16 dB, respectively. It should be emphasized that the present array has the widest axial ratio bandwidth in coplanar series-fed element arrays above the ground plane.

ACKNOWLEDGMENT

The authors thank Blair Thomson and Naonoshin Ito for their assistance in preparing this manuscript.

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