Progress In Electromagnetics Research M, Vol. 115, 59–69, 2023

Fundamental Study on Comb-Line Antennas Modified with Loop Elements for Increased Axial Ratio Bandwidth

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Abstract—We study three comb-line antennas to increase the bandwidth for a 3 dB axial ratio criterion. Each antenna comprises linear radiation elements with loops and a coplanar feedline above the ground plane. First, we analyze a reference antenna with a straight feedline using the method of moments. Next, the straight feedline is transformed into a round one for a sequential rotation technique. It is found that the antenna has an increased bandwidth of 30%, which is three times as wide as that of the reference antenna. Last, we propose a novel antenna with a straight feedline. It is revealed that the antenna shows a 3 dB gain drop bandwidth of 29% (40% for the axial ratio bandwidth). The simulated results are validated by experimental work.

1. INTRODUCTION

A comb-line antenna above the ground plane has been designed for circularly polarized (CP) radiation [1, 2]. The antenna comprises linear radiation elements branching from a coplanar straight feedline, having the advantage of a simple series-fed array [3–6]. The antenna can radiate a CP wave using a sequential rotation (SR) technique [3, 4] or with the help of CP loop elements [5, 6].

This paper is a sequel to the previous one [6] and presents a recent development in a comb-line antenna with CP loop elements. We modify the antenna using the SR technique to increase the CP wave bandwidth. The radiation characteristics are evaluated using the current distribution determined by the method of moments [7].

It is the first time to discuss the effects of different comb-line configurations with SR [see Figures 1(b) and (c)] on CP radiation. The discussion aids in designing and understanding a comb-line antenna. Furthermore, we propose a novel comb-line antenna shown in Figure 1(c) and find a critical parameter for wideband CP radiation [angle τ in Figure 5(b)'s inset]. The technical novelty of this paper is that we can obtain the widest axial ratio bandwidth for the proposed comb-line antenna (see Table 1) by finding the critical parameter τ. Note that the present antenna does not require a matched termination [1, 2], resulting in a higher gain even for a small number of radiation elements.

This paper first presents the radiation characteristics of a reference antenna [6], shown in Figure 1(a). Next, we transform the reference antenna's straight feedline into a round one, as shown in Figure 1(b). Finally, we propose a novel comb-line antenna with a straight feedline which is shown in Figure 1(c) and discuss the radiation characteristics.

2. REFERENCE ANTENNA AND ANALYSIS METHOD

Figure 1(a) shows a reference antenna at a height h above the ground plane. The comb line consists of a straight feedline F-T and N linear radiation elements of length L_R at a distance d. The feedline

Received 30 December 2022, Accepted 3 February 2023, Scheduled 8 February 2023
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F-T is excited from the left end F via a vertical wire F-F' using a coaxial line, and the other end T is open-circuited.

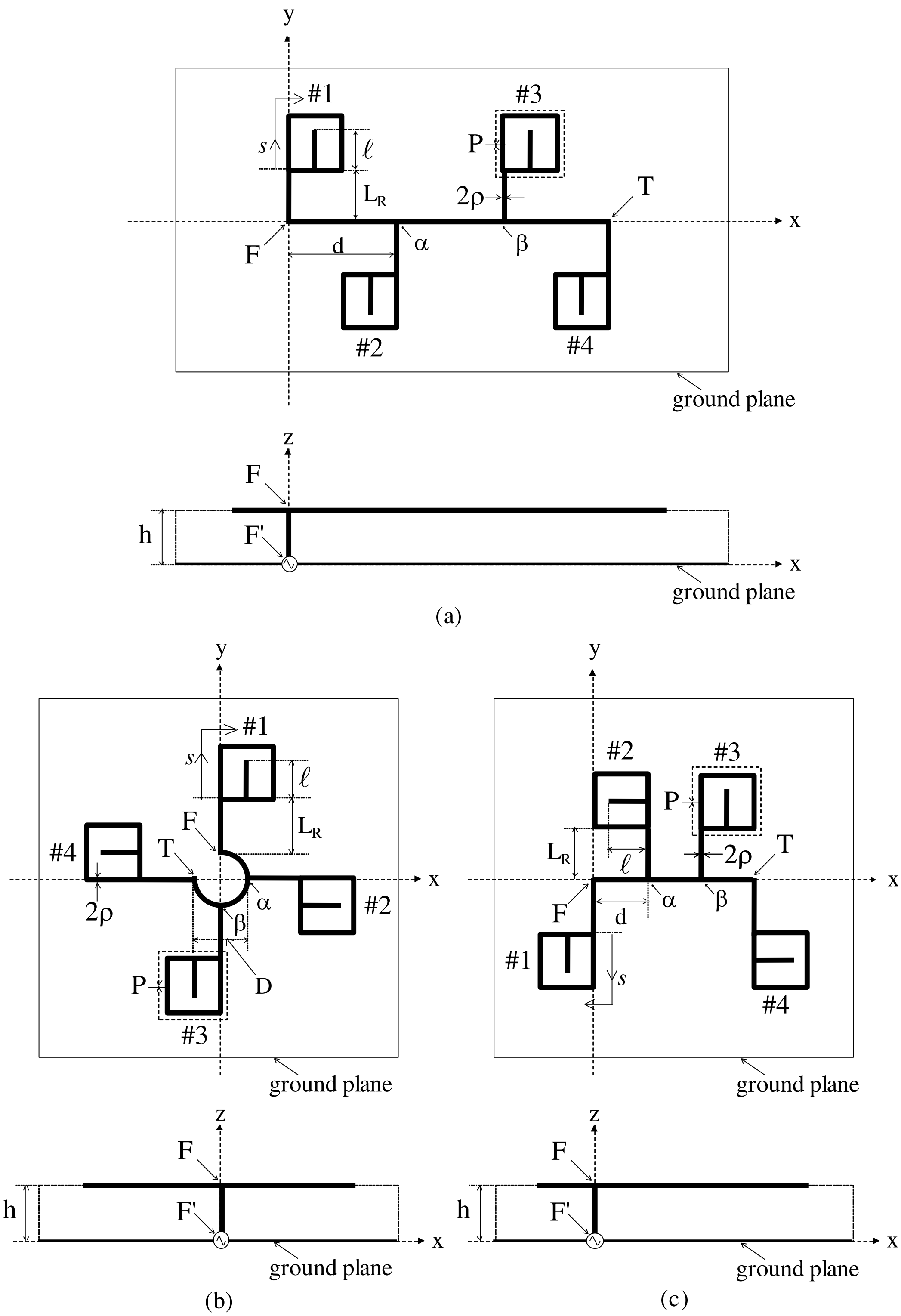


Figure 1. Antennas with a coplanar feedline F-T. (a) Reference antenna [6]. (b) Round feedline antenna. (c) Straight feedline antenna.

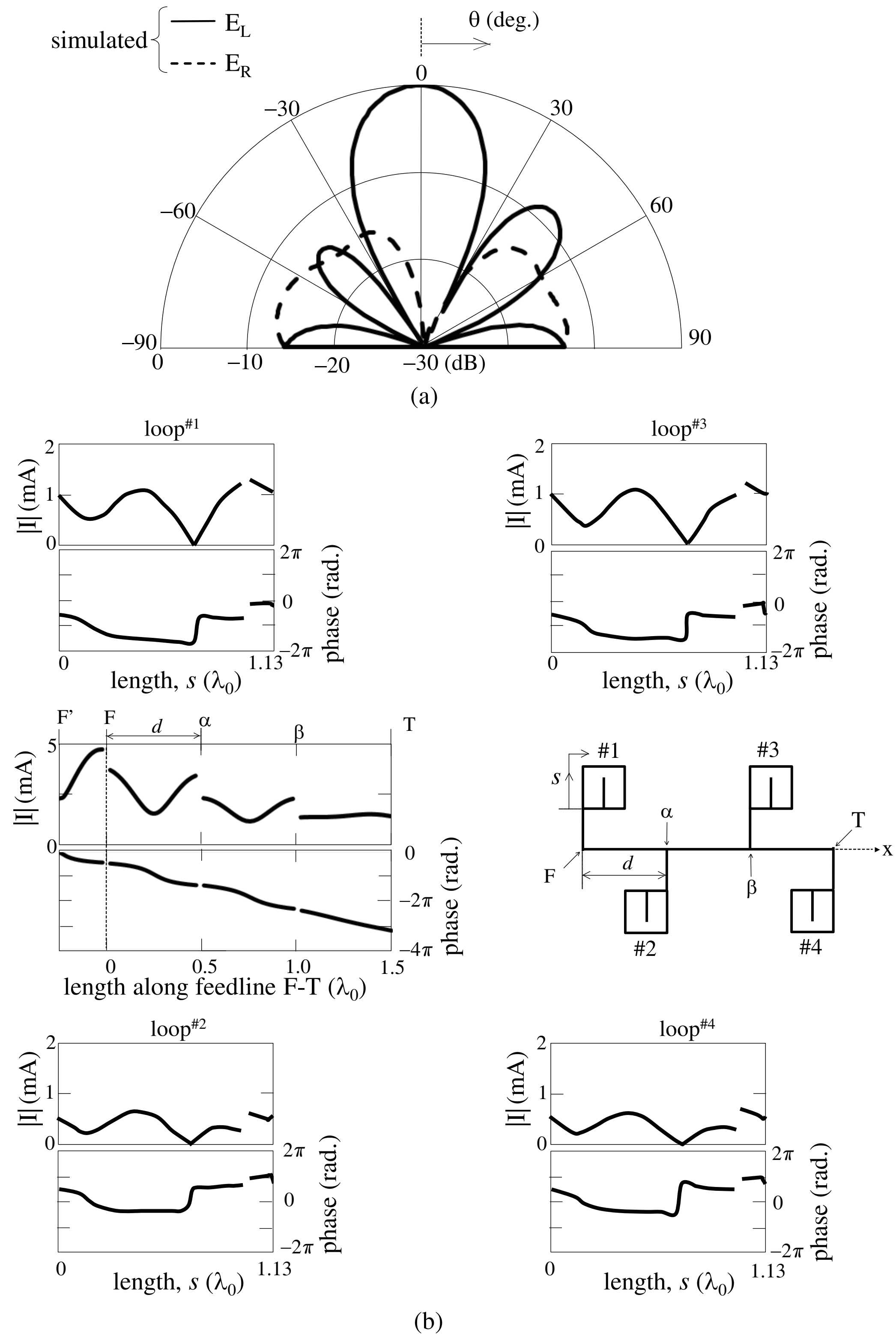


Figure 2. Simulated results of a reference antenna. (a) Radiation pattern in the $\phi = 0°$ plane. (b) Current distributions with $|I|$ denoting the current amplitude.

We add a square loop of perimeter P with a stub of length ℓ to each extremity of the linear element for CP radiation [6, 8]. The antenna is made of wires of a radius ρ [6, 8, 9]. Note that the loop orientations on the $+y$ side differ from those on the $-y$ side by 180°. Also, note that we define loop orientation as the direction in which the loop-stub tip points, e.g., the orientation of a loop on the $+y$ side in Figure 1(a) is in the $+y$ direction.

We analyze the antenna using the method of moments [7, 9], where the ground plane is assumed to be of an infinite extent. The antenna is designed to radiate a CP beam in a direction normal to the antenna plane in the $+z$-axis direction. For this, we select the linear element's distance and loop parameters (d, P, ℓ). The other configuration parameters are taken to be the same as those in [6]: (h, N, L_R, ρ) = ($\lambda_0/4$, 4, $\lambda_0/4$, $\lambda_0/200$), where λ_0 is the free-space wavelength at a test frequency of f_0.

Figure 2(a) shows the simulated radiation pattern for (d, P, ℓ) = ($0.50\lambda_0$, $1.13\lambda_0$, $0.22\lambda_0$). The radiation is decomposed into right- (E_R) and left-hand (E_L) CP wave components, shown with dotted and solid lines. It is seen that a left-hand CP beam is formed in the $+z$-axis direction. The half-power beamwidth (HPBW) is 26°, and the gain is 12.1 dBi.

The current distributions are shown in Figure 2(b). The first and third rows are the currents of loops #1 and #3 (loops$^{\#1,3}$) and those of loops$^{\#2,4}$, respectively, with the second row's feedline current. It is observed from the second row that the feedline current is a traveling-wave type, as expected. The phase varies almost linearly by 180° along each length of $d = 0.50\lambda_0$ (see the inset). This current excites loops$^{\#1,3}$ and loops$^{\#2,4}$ with a phase difference of 180°, as confirmed by the phases of the loop currents shown in the first and third rows.

A question arises from the above-mentioned phase difference (180°) between loops$^{\#1,3}$ and loops$^{\#2,4}$. Why does the antenna radiate a beam normal to the antenna plane? To answer the question, recall the difference between the loop orientations mentioned in Figure 1(a). Since loops$^{\#1,3}$ are rotated by 180° with respect to loops$^{\#2,4}$, this loop rotation compensates for the excitation phase difference of 180°, leading to the normal beam formation.

3. ROUND FEEDLINE ANTENNA

In Section 2, a normal beam has been formed due to a loop rotation of 180°. This section sequentially rotates loops by 90° for wideband CP radiation.

Figure 1(b) shows the antenna configuration. We transform the straight feedline F-T of the reference antenna into a round one of diameter D to orient loops$^{\#1,2,3,\text{ and }4}$ in the $+y$, $+x$, $-y$, and $-x$ directions, respectively. The other configurations are the same as those of the reference antenna. Note that the round feedline consists of F-α, α-β, and β-T arcs, each having a path length of d.

The above-mentioned sequential rotation (SR) makes the phase of partial radiation from each loop lead since the loop radiates a left-hand CP wave, as shown in Figure 2(a). To make the partial radiation phases the same, we take each arc length in the round feedline to be $d = \lambda_0/4$, resulting in a round-feedline diameter of $D = \lambda_0/\pi$.

The simulated radiation pattern for (d, P, ℓ) = ($0.25\lambda_0$, $1.10\lambda_0$, $0.25\lambda_0$) is shown in Figure 3(a). It is seen that the antenna radiates a CP beam in the $+z$-axis direction. The HPBW is 37°, and the gain is 11.9 dBi.

Figure 3(b) shows the current distributions. It is observed from the second row that the feedline current is a traveling-wave type as that of the reference antenna. The phase delays by 90° along each arc length of $d = \lambda_0/4$. This current excites loops$^{\#1,2,3,\text{ and }4}$ with phase differences of 0°, −90°, −180°, and −270°, respectively. We can confirm these phase differences by observing the loop currents shown in the first and third rows. The excitation phase delay compensates for the progress in the partial radiation phase by the loop rotation, leading to the radiation beam being normal to the antenna plane, as shown in Figure 3(a).

The SR enlarges the CP wave bandwidth. This is shown in Figure 4, where the simulated axial ratio versus frequency is compared with the reference antenna's. It is found that the present antenna shows a 3 dB axial ratio bandwidth of 30%, which is three times as wide as that (9%) of the reference antenna. The Figure also shows a comparison between the gains. The present antenna has a gain of more than 9.6 dBi in the CP wave bandwidth, while the reference antenna's gain is more than 11.5 dBi in its bandwidth.

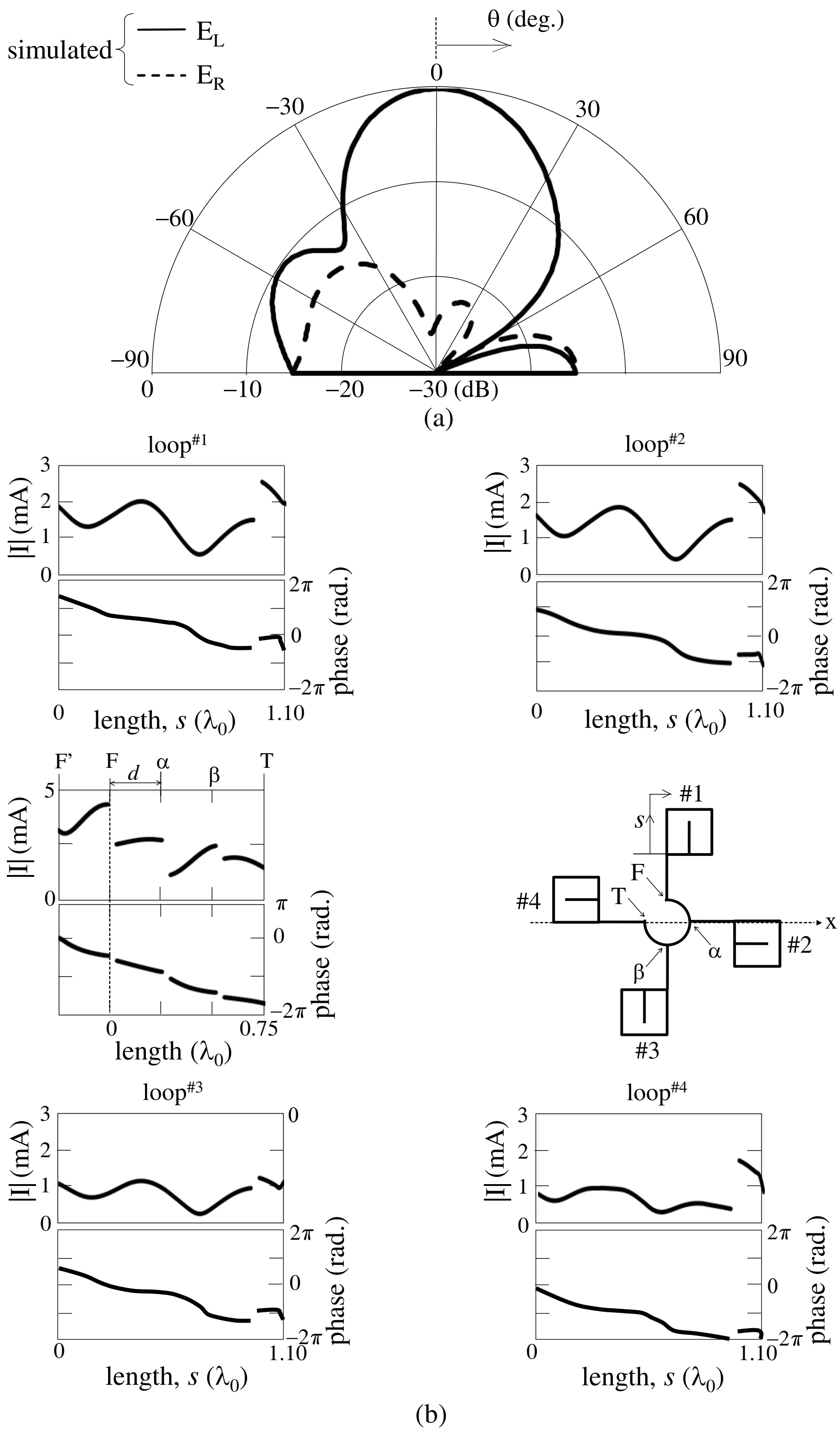


Figure 3. Simulated results of a round feedline antenna. (a) Radiation pattern in the $\phi = 0°$ plane. (b) Current distributions with $|I|$ denoting the current amplitude.

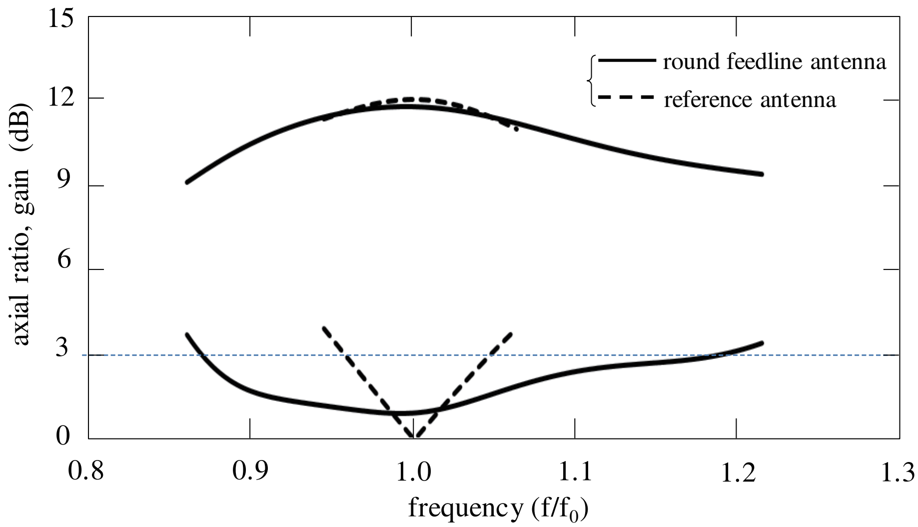


Figure 4. Simulated frequency responses of the axial ratio and gain at $\theta = 0°$ for a round feedline antenna.

4. STRAIGHT FEEDLINE ANTENNA

We have sequentially rotated the loops by 90° using a round feedline in Section 3. This section proposes a novel comb-line antenna, which realizes an SR of 90° using a straight feedline.

Figure 1(c) shows the antenna configuration. The orientations of loops$^{\#1,2,3,\text{and }4}$ are $-y$, $-x$, $+y$, and $+x$ directions, respectively. To compensate for the phase lead of partial radiation from each loop, we take the linear element distance to be $d = \lambda_0/4$. The other configurations are the same as those of the reference antenna.

Preliminary calculations show that the CP wave bandwidth is smaller than expected. One of the reasons would be a smaller distance between the loops $^{\#2,3}$, as shown in Figure 1(c). We then increase this distance by tilting their linear elements with an angle τ defined in Figure 5(b) inset and analyze the antenna.

Figure 5(a) shows the simulated radiation pattern for $\tau = 50°$ with $(d, P, \ell) = (0.25\lambda_0, 1.00\lambda_0, 0.20\lambda_0)$. We see that the antenna radiates a CP beam in the $+z$-axis direction. The HPBW is 32°, and the gain is 10.7 dBi.

The current distributions are shown in Figure 5(b). It is seen that the feedline current is a traveling-wave type as a reference antenna. We also observe from the loop currents that loops$^{\#1,2,3,\text{and }4}$ have phase differences of 0°, −90°, −180°, and −270°, respectively, resulting in the normal beam shown in Figure 5(a).

The simulated frequency responses of the axial ratio and gain are shown with solid lines in Figure 6. A 3 dB gain drop bandwidth is found to be 29%, where the axial ratio is less than 3 dB (the axial ratio bandwidth is 40%). It is emphasized that the antenna shows a wider bandwidth than the reference antenna by a factor of 3.

Finally, consideration is given to the input impedance matching the coaxial line. For this, we modify a straight wire F-F' which is shown in Figure 1(c) into a crank one shown in the inset of Figure 7. The crank configuration is specified by parameters (ℓ_1, ℓ_2), which are empirically determined to be $(\ell_1, \ell_2) = (0.025\lambda_0, 0.20\lambda_0)$ so that the modification does not deteriorate the radiation characteristics for the straight wire F-F'. Note that the other antenna parameters are held at the same values as those for the straight wire F-F'.

The simulated voltage standing wave ratio (VSWR) versus frequency is shown with a solid line in Figure 7, together with the gain and axial ratio. The VSWR is evaluated for a 50 Ω coaxial line. It is found that the VSWR remains less than 2 in a gain drop bandwidth of 30%, where the axial ratio is less than 3 dB. The solid and dotted lines in Figure 8 show a simulated radiation pattern similar to that for the straight wire F-F' [see Figure 5(a)].

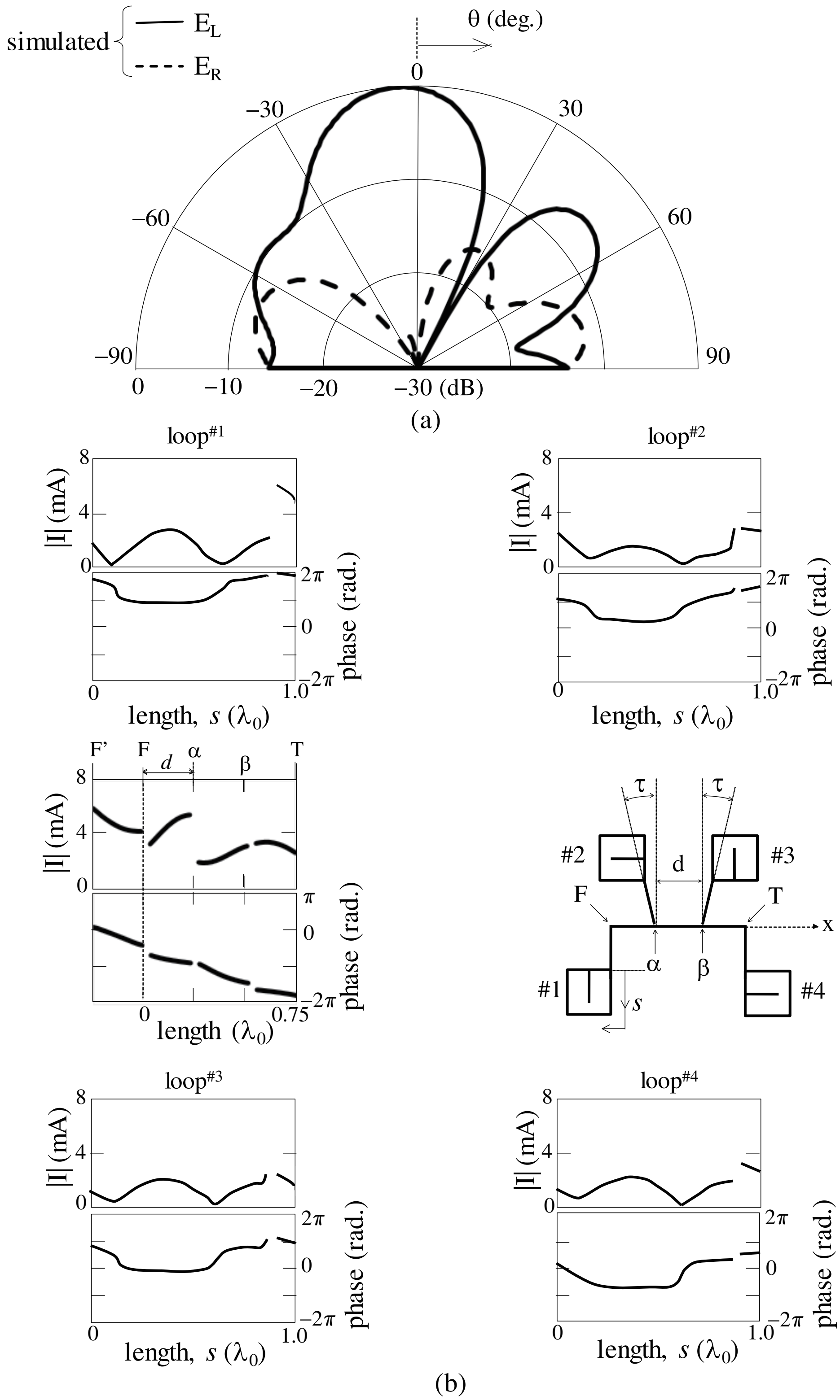


Figure 5. Simulated results of a straight feedline antenna. (a) Radiation pattern in the $\phi = 0^\circ$ plane. (b) Current distributions with $|I|$ denoting the current amplitude.

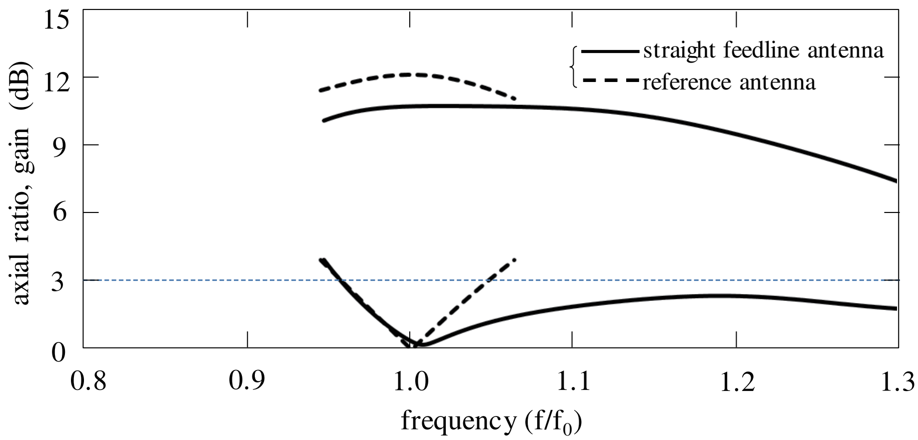


Figure 6. Simulated frequency responses of the axial ratio and gain at $\theta = 0°$ for a straight feedline antenna.

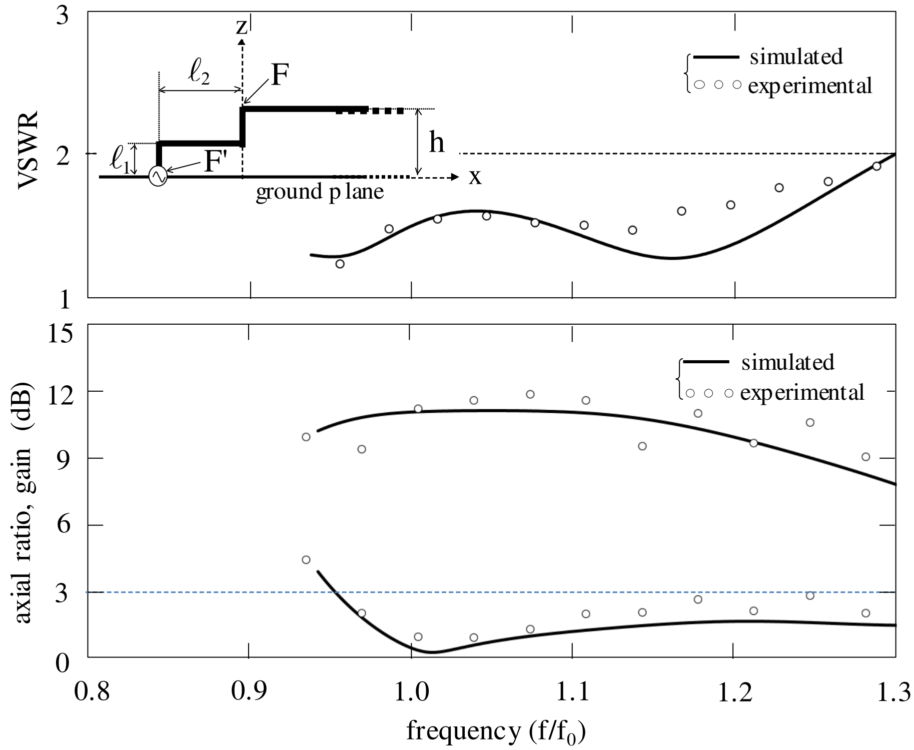


Figure 7. Frequency responses of VSWR, axial ratio, and gain of a straight feedline antenna with a crank wire F-F'.

So far, we have shown the simulated results. To validate the results, we fabricate an antenna at $f_0 = 3\,\text{GHz}$ using the ground plane of $5\lambda_0 \times 5\lambda_0$. The antenna's photographs are shown in Figure 9. The experimental results are shown with small circles and dots in Figures 7 and 8, which agree well with the simulated results.

Before conclusion, it is necessary to compare our results using a crank wire F-F' with those of other comb-line antennas, together with array antennas with SR [10–12]. Comparisons are summarized in Table 1. It is emphasized that the present antenna has the widest axial ratio bandwidth. The reason for the widest bandwidth is in a method for CP wave radiation in the right-most column: The present antenna has loop elements with an enlarged bandwidth of circular polarization in itself [6], and we can

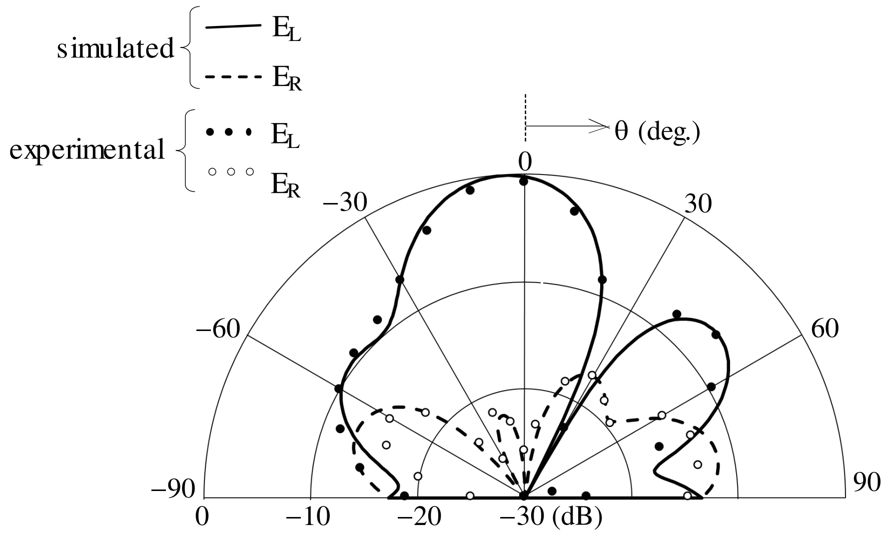


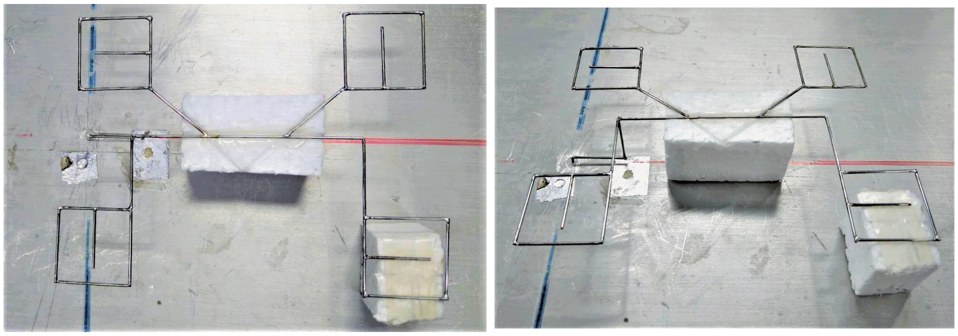
Figure 8. Radiation pattern in the $\phi = 0°$ plane for a straight feedline antenna with a crank wire F-F'.

Table 1. Comparisons with other studies.

Antenna	**Study**	**Array type**	**AR < 3 dB BW (%)**	**Gain (dBi)**	**OF (GHz)**	**RE (%)**	**Antenna size $x \times y \times z(\lambda_0^3)$ (z: Thickness)**	**Method for CP wave radiation**
Comb-line antenna	[3]	(1 × 8) × 15	4	17.7	24	−4.3 dB	17.0 × 8.0 × 0.1	LP patch with SR
	[4]	1 × 12	13	12.5	8	–	6.0 × 1.0 × 0.03	LP patch with SR
	[14]	1 × 24	4	17.0	86	70.5	16.3 × 0.6 × 0.04	LP patch with SR
	[15]	1 × 10	4.0*	10.0	9.75	60	5.1 × 0.3 × 0.02	LP patch with SR
	present	1 × 4	30	11.0	3	≈ 100	1.3 × 0.9 × 0.25	LP element and CP loop with SR
Array antenna with SR	[10]	4 × 4	14*	19.24	29	85	4.8 × 4.8 × 1.7	CP patch
	[11]	4 × 4	23.8	20.5	64	87.7	4.4 × 8.5 × 0.5	CP patch
	[12]	8 × 8	18.3	18.5	25	66.8	5.6 × 5.6 × 0.09	CP patch
	[16]	2 × 2	20.4	11.1	27	–	2.9 × 2.9 × 0.1	CP patch
	[17]	2 × 2	18.9	13.8	5.6	–	−× −×0.1	CP stacked patch

(SR): Sequential rotation; (AR): Axial ratio; (BW): Bandwidth; (OF): Operating frequency; (RE): Radiation efficiency; (LP): Linearly polarized; (CP): Circularly polarized; (*): 1.5 dB AR bandwidth; (–): not described

further apply SR to the CP loop elements. In contrast, a conventional comb-line antenna has linearly polarized (LP) patch elements with SR for CP radiation. Note that the radiation efficiency of the present antenna is almost 100% since there are only conductor losses that are negligible up to a 12 GHz band [13]. Namely, we do not use a lossy-matched termination and a conventional dielectric substrate that involves dielectric and surface-wave losses [13].



(a) (b)

Figure 9. Photographs of a straight feedline antenna with a crank wire F-F'. (a) Top view. (b) Perspective view.

5. CONCLUSION

We have designed comb-line antennas modified for wideband CP radiation. Each antenna is located above the ground plane at a height of $\lambda_0/4$. It is found that round and straight feedline antennas with a sequential rotation (SR) show a 3 dB axial ratio bandwidth of 30% and a 3 dB gain drop bandwidth of 29%, respectively. We emphasize that the angle τ of the straight feedline antenna with an SR is a critical parameter for wideband CP radiation.

Based on the present fundamental study, future studies should examine gain enhancement in frequencies more than 8 GHz, and the lowest frequencies of other studies on comb-line antennas are shown in Table 1.

ACKNOWLEDGMENT

The authors would like to thank Blair Thomson for his invaluable assistance in the preparation of this manuscript.

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