Steering of the Circularly Polarized Beam from a Spiral Antenna

Tomoki Abe\(^{1a)}\), Junji Yamauchi\(^{1}\), and Hisamatsu Nakano\(^{1}\)

\(^{1}\)Science and Engineering, Hosei University
Kajino-cho, Koganei-shi, Tokyo 184-8584, Japan
\(^{a)}\)tomoki.abe.5r@stu.hosei.ac.jp

Abstract: The circularly polarized axial and conical beams from a two-arm spiral antenna are investigated and the radiation phase distributions around the antenna axis are clarified. A tilted beam is created by superimposing the conical beam onto the axial beam. The tilted beam is steered in the azimuth plane when the two arms are excited by different amplitudes and phases. The beam direction of the tilted beam estimated using formulated phase distributions agrees with that obtained from a numerical analysis. The estimation with the formulated phase is simple and has the superiority over the determination of the complex and time-consuming numerical analysis.

Keywords: beam-steering, circularly polarized wave, spiral antenna

Classification: Antennas and Propagation

1 Introduction

Modern communication systems often require an antenna system that has a circularly polarized (CP) beam-steering function. For this, reconfigurable antennas have been proposed, \textit{e.g.}, in \cite{1} and \cite{2}. In these antennas, the CP beam-steering in the azimuth plane is achieved by selecting an activated element with a switching
circuit. Note that the antenna systems in [1] and [2] have four feed points. A question arises as to whether CP beam-steering can be performed using two feed points. If this is achieved, we have a CP beam-steering antenna with a simple structure. From this background, we present a CP beam-steering antenna based on a two-arm Archimedean spiral antenna [3]. A simple formula for estimating the beam direction is derived.

2 Antenna Configuration

Fig. 1 shows the configuration of a two-arm Archimedean spiral antenna. The two spiral arms are printed on a dielectric substrate of relative permittivity \( \varepsilon_{\text{sub}} = 2.6 \) and thickness \( B = 0.8 \text{ mm} \). The dielectric substrate is placed above a conducting cavity whose diameter is \( D_{\text{CAV}} = 82 \text{ mm} = 1.23\lambda_0 \), and height is \( H_{\text{CAV}} = 7.0 \text{ mm} = 0.105\lambda_0 \) with \( \lambda_0 \) being the free-space wavelength at a design frequency of 4.5 GHz. The radial distance from the coordinate origin to the centerline of the spiral arm, \( r_{\text{arm}} \), is defined by the Archimedean function \( r_{\text{arm}} = a_{\text{sprl}}\phi_{\text{wnd}} \), where \( a_{\text{sprl}} \) is the arm growth constant and \( \phi_{\text{wnd}} \) is the winding angle: \( a_{\text{sprl}} = 1.273 \text{ mm/rad} \) and \( 0.5\pi \text{ rad} \leq \phi_{\text{wnd}} \leq 8.5\pi \text{ rad} \). The arm width is \( w = 2.0 \text{ mm} \). Two feed points of the spiral arms, \( F_1 \) and \( F_2 \), are excited by voltage sources \( V_1 \) volt and \( V_2 \) volt, respectively. A small conducting disc behind the spiral arms has a diameter of \( 2r_{\text{disc}} = 12.0 \text{ mm} \). The distance from the spiral plane to the small disc is \( d_{\text{disc}} = 1.0 \text{ mm} \). To decrease undesirable reflection currents from the spiral arm ends, a ring-shaped absorber (ABS, ISFA_EM, TDK production: relative permittivity \( \varepsilon_{\text{abs}} = 1.92 \) and \( \tan\delta = 1.15 \) at 4.5 GHz) is placed along the cavity wall. The thickness of the absorber is \( t_{\text{abs}} = 11.0 \text{ mm} \).

![Fig. 1. Configuration of a two-arm Archimedean spiral antenna.](image-url)
3 CP Beam-Steering

A CP beam-steering with the spiral antenna is discussed in this section. Note that the results in this section are those obtained using an electromagnetic analysis solver (CST [4]).

First, we clarify the basic radiation from the spiral antenna. Fig. 2(a) shows the radiation pattern at a design frequency of 4.5 GHz when the feed points $F_1$ and $F_2$ are excited in balanced mode ($V_1 = 1\angle 0^\circ$, $V_2 = 1\angle 180^\circ$). The red solid line denotes the co-polarized component (right-handed CP component $E_R$) of the radiation and the blue dotted line denotes the cross-polarized component (left-handed CP component $E_L$). The co-polarized component $E_R$ is radiated in the broadside direction ($+z$-direction). The amplitude $|E_{RH-bal}|$ and phase $\angle E_{RH-bal}$ of the $E_R$ in

![Graph showing balanced mode radiation](image)

(b) Balanced mode amplitude $|E_{RH-bal}|$ and phase $\angle E_{RH-bal}$

(c) Unbalanced mode radiation

(d) Unbalanced mode amplitude $|E_{RH-unbal}|$ and phase $\angle E_{RH-unbal}$

(e) Tilted beam

(f) Phase difference $\angle E_{RH-unbal} - \angle E_{RH-bal}$

(g) Beam direction of CP wave from the spiral antenna

Fig. 2. Radiation field from the spiral antenna at a design frequency of 4.5 GHz.
balanced mode are shown in Fig. 2(b), where the spherical coordinate angle $\theta$ is fixed to be a representative value of $\theta = 30^\circ$. It is found that $|E_{RH-bal}|$ is almost unchanged around the antenna axis ($z$-axis), while $\angle E_{RH-bal}$ changes by $360^\circ$ in an almost linear fashion.

Fig. 2(c) shows the basic radiation pattern at 4.5 GHz when the feed points $F_1$ and $F_2$ are excited in unbalanced mode ($V_1 = 1 \angle 0^\circ$, $V_2 = 1 \angle 0^\circ$). The maximum radiation intensity of the co-polarized component $E_R$ appears off the $z$-axis. The amplitude $|E_{RH-unbal}|$ and phase $\angle E_{RH-unbal}$ of the $E_R$ are shown in Fig. 2(d). The gradient of the $\angle E_{RH-unbal}$ differs from that of the $\angle E_{RH-bal}$, i.e., $\angle E_{RH-unbal}$ changes by $720^\circ$ in an almost linear fashion around the $z$-axis.

Second, we superimpose the basic unbalanced mode radiation onto the basic balanced mode radiation. The superimposition forms a tilted beam at azimuth angle $\phi = 0^\circ$, i.e., in the $+x$-direction, as shown in Fig. 2(e). This is due to the fact that difference in the phases of the basic balanced mode radiation and basic unbalanced mode radiation becomes zero at $\phi = 0^\circ$, as shown in Fig. 2(f), i.e., the two mode radiation phases are in-phase.

Third, we consider beam-steering. For this, the voltages at feed points $F_1$ and $F_2$ are changed, as shown in Eq. (1).

$$(V_1, V_2)^T = (1 \angle 0^\circ, r \angle (180^\circ + \delta))^T$$

where $T$ denotes the transposition operator of a matrix, $r$ is called the excitation voltage amplitude, and $\delta$ is called the deviation angle. Fig. 2(g) shows the maximum radiation azimuth angle, $\phi_{RH-max-CST}$, when $r$ is varied and $\delta$ is fixed to be $\pm 90^\circ$. The red and blue dots are for $\delta = +90^\circ$ and $\delta = -90^\circ$, respectively. Thus, the CST analysis reveals that the CP beam is steered in the azimuth plane with change in $r$.

### 4 Estimation for the Beam Direction

In the previous section, CP beam-steering with the spiral antenna is performed, where the beam direction is determined by the electromagnetic analysis solver CST. In this CST analysis, first, we analyzed 3D radiation pattern for each $r$. Second, we searched the beam direction from the obtained 3D radiation pattern. Note that the numerical analysis is repeated for each $r$. This process is quite time-consuming. In this section, we present a simple formula for estimating the beam direction.

We decompose Eq. (1) into a balanced mode component $V_{bal}$ and an unbalanced mode component $V_{unbal}$.

$$V_{bal} = A_{bal} \angle \phi_{bal}$$  \hspace{1cm} (2)$$

$$V_{unbal} = A_{unbal} \angle \phi_{unbal}$$  \hspace{1cm} (3)$$

where $A_{bal}$ and $\phi_{bal}$ are called the balanced mode excitation amplitude and phase, respectively; and $A_{unbal}$ and $\phi_{unbal}$ are called the unbalanced mode excitation amplitude and phase, respectively. We choose $\delta$ to be $\pm 90^\circ$ to obtain $A_{bal} = A_{unbal}$. The following relationships are held for $\delta = \pm 90^\circ$.

$$A_{bal} = A_{unbal} = \frac{\sqrt{1+r^2}}{2}$$  \hspace{1cm} (4)$$
\[ \phi_{\text{bal}} = \tan^{-1}(\pm r) \quad \text{for } \delta = \pm 90^\circ \] (5)

\[ \phi_{\text{unbal}} = \tan^{-1}(\mp r) \quad \text{for } \delta = \pm 90^\circ \] (6)

The difference of \( \phi_{\text{unbal}} \) relative to \( \phi_{\text{bal}} \) is defined as mode phase difference \( \Delta \phi \). From Eqs. (5) and (6), \( \Delta \phi \) is expressed as Eq. (7).

\[ \Delta \phi \equiv \phi_{\text{unbal}} - \phi_{\text{bal}} = \tan^{-1}\left( \mp \frac{2r}{1-r^2} \right) \quad \text{for } \delta = \pm 90^\circ \] (7)

That is, \( \Delta \phi \) is varied with \( r \). Note that \( \angle \text{ERH-bal} \) in Fig. 2(b) and \( \angle \text{ERH-unbal} \) in Fig. 2(d) are obtained for a situation of \( (r = 1, \Delta \phi = 0) \).

We estimate a maximum radiation azimuth angle of \( \phi_{\text{RH-max}} \). The maximum radiation component \( E_R \) appears when Eq. (8) is satisfied.

\[ \angle \text{ERH-unbal}(\phi_{\text{RH-max}}) + \Delta \phi = \angle \text{ERH-bal}(\phi_{\text{RH-max}}) \] (8)

As shown in Fig. 2(b), the basic balanced mode radiation phase \( \angle \text{ERH-bal}(\phi) \) changes by 360° in an almost linear fashion. Therefore, \( \angle \text{ERH-bal} \) is approximated as Eq. (9).

\[ \angle \text{ERH-bal}(\phi) = -\phi + \angle \text{ERH-bal}(0) \] (9)

where \( \angle \text{ERH-bal}(0) \) denotes the phase of the basic balanced mode radiation at an azimuth angle of \( \phi = 0^\circ \).

On the other hand, the basic unbalanced mode radiation phase \( \angle \text{ERH-unbal}(\phi) \) changes by 720° in an almost linear fashion, as shown in Fig. 2(d). This is approximated as Eq. (10).

\[ \angle \text{ERH-unbal}(\phi) = -2\phi + \angle \text{ERH-unbal}(0) \] (10)

Substituting Eqs. (7), (9), and (10) to Eq. (8), \( \phi_{\text{RH-max}} \) is given by

\[ \phi_{\text{RH-max}} = \angle \text{ERH-unbal}(0) - \angle \text{ERH-bal}(0) + \tan^{-1}\left( \frac{2r}{1-r^2} \right) \quad \text{for } \delta = \pm 90^\circ \] (11)

where \( \angle \text{ERH-bal}(0) \) and \( \angle \text{ERH-unbal}(0) \) are given by the values for the blue dotted lines at \( \phi = 0^\circ \) in Figs. 2(b) and (d), respectively.

To confirm the validity of Eq. (11), we compare the formulated value \( \phi_{\text{RH-max}} \) with the CST value \( \phi_{\text{RH-max-CST}} \). The solid line in Fig. 2(g) shows \( \phi_{\text{RH-max}} \) for \( \delta = +90^\circ \) and the broken line shows \( \phi_{\text{RH-max}} \) for \( \delta = -90^\circ \). There is good agreement between \( \phi_{\text{RH-max}} \) and \( \phi_{\text{RH-max-CST}} \) for both \( \delta \) cases. Thus, the validity of Eq. (11) is confirmed. Note that the solid line and broken line are symmetric with respect to a dotted line, \( \angle \text{ERH-unbal}(0) - \angle \text{ERH-bal}(0) \), which is specified by symbols (x) in Fig. 2(g). The estimation of the beam direction by Eq. (11) is simple and leads to less computational burden, compared with the repeated CST numerical analysis.

For additional observation, the CST numerical and experimental radiation patterns in the azimuth plane (at \( \theta = 30^\circ \)) are shown in Fig. 3, where \( \delta \) is fixed to be +90°. It is clear that the CP beam is steered in the azimuth plane with change in \( r \). The experimental results agree with the CST numerical analysis results.

Some comments are made here. (1) the beam direction in the elevation plane \( \theta_{\text{RH-max-CST}} \) is almost constant when the beam is rotated around the antenna axis. This is attributed to the fact that \( A_{\text{bal}} \) equals \( A_{\text{unbal}} \) irrespective of the value of \( r \) for \( \delta = \pm 90^\circ \). (2) the equalization of \( A_{\text{bal}} \) to \( A_{\text{unbal}} \) infers that the gain and axial ratio
(AR) in the beam direction will be almost constant. The gain is approximately 7.0 dBi and the AR is approximately 0.8 dB. (3) the voltage standing wave ratio (VSWR) is less than two around the design frequency.

5 Conclusion

Steering of the CP beam from a two-arm spiral antenna has been discussed. First, the radiation in balanced and unbalanced modes from the spiral antenna has been analyzed. Second, the phase distributions for these two modes have been formulated. Third, using the formulated phase distributions, we have derived a simple formula that estimates the steered beam direction \( \phi_{\text{RH-max}} \) in the azimuth plane. The derived formula provides a good estimation for \( \phi_{\text{RH-max}} \). The formula is simple and less computational burden, compared with the repeated numerical analysis using a commercial EM solver.

Fig. 3. Radiation pattern in the azimuth plane where \( r \) is changed and \( \delta \) is fixed to be +90°.