Realization of a Circularly Polarized Tilted Beam

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1. Introduction

Most patch antennas are designed such that the maximum radiation is in the direction normal to the patch plane (z-direction). When a tilted beam is required for a communications system (such as a mobile communications system), the tilted beam can be obtained by arraying a number of patches in the horizontal plane (x-y plane) and configuring an appropriate feed phase relationship. Clearly, the space occupied by this array is larger than that for a single patch element.

Development of an antenna that radiates a tilted beam without phase shifters has been receiving much attention. We have proposed a tilted beam antenna (BeFoL)\[1\][2], shown in Fig. 1(a), where no phase shifters are used. The BeFoL has a horizontal area of \( s_x \times s_y = 0.64 \) wavelength \( \times 0.46 \) wavelength, which is comparable to the patch antenna size. The tilted radiation beam from the BeFoL is linearly polarized (LP) and the input-impedance bandwidth is relatively wide (44%). Note that a BeFoL in Fig. 1(b) [3] is a simplified version of the BeFoL.

We have also proposed an antenna that radiates a tilted circularly polarized (CP) wave [4]. As shown in Fig. 1(c), this proposed antenna comprises a single spiral arm that has first-mode and second-mode active regions [5]. The diameter of this antenna is 0.73 wavelength to support the second-mode active region. Note that a tilted CP wave is radiated over a wide input impedance bandwidth.

A question arises as to what structure can radiate a tilted CP wave and have a small horizontal size of less than 0.73 wavelength. This paper presents one answer to this question using a composite structure of helical and spiral arms. This antenna is designated as the CHES. The analysis and discussion of the CHES is performed for an antenna diameter of 0.56 wavelength (76.7% reduction from the spiral structure). In addition to the analysis of the CHES, an array antenna composed of CHES elements is also analyzed.

2. Configurations

Fig. 2 shows the composite helical and spiral (CHES) antenna to be considered in this paper. The helical arm section is specified by the helix radius \( r_{Hx} \), helix pitch angle \( \alpha_{Hx} \), and number of helical turns \( N_{Hx} \). The spiral arm section is defined by an equiangular spiral function, where the winding angle ranges from \( \phi_s \) to \( \phi_{end} \).

The helix radius, number of helical turns, and start angle are chosen to be \( r_{Hx} = 0.28 \) wavelength, \( N_{Hx} = 1 \), and \( \phi_s = 2\pi \) rad, respectively, and fixed throughout this paper. The pitch angle \( \alpha_{Hx} \) and end angle of the spiral \( \phi_{end} \) are varied subject to the objectives of the analysis. Note that the ground plane (GP) is assumed to be of infinite extent in the following theoretical analysis.

3. Discussion

3.1 Effects of the end angle of the spiral arm and the helix pitch angle on the radiation

The current on the CHES wire is analyzed using the method of moments [6] over a frequency range of 11.5 GHz to 13.0 GHz. The analysis shows that, as the end angle \( \phi_{end} \) is increased, the decay in the amplitude of current becomes smoother. This means that the reflected current travelling from the arm end toward the feed point decreases with an increase in \( \phi_{end} \). From this behaviour of the current, it is expected that, as the end angle \( \phi_{end} \) is increased, the radiation will
become circularly polarized. This expectation is confirmed in Fig. 3, which illustrates a representative tilted radiation pattern for $\phi_{\text{end}} = 6\pi$ rad at a test frequency $f_t = 12.225$ GHz (wavelength $\lambda_{12.225} = 24.5$ mm). Note that $E_R$ in this figure shows a right-hand CP wave component and $E_L$ shows a left-hand CP wave component.

The generation of the tilted beam can be explained using the currents distributed along the helical and spiral arms. The radiation fields calculated from these currents reveal that, in the $\theta = \theta_{\text{max}}$ direction, the phases of $\phi_R$ relevant to the radiation fields from the helix and spiral are approximately in-phase. However, in the $\theta = \theta_{\text{null}}$ direction, the phases of $\phi_R$ are approximately out-of-phase. Due to these phase relationships, the total radiation field forms a tilted beam, as shown in Fig. 3.

The effect of the helix pitch angle $\alpha_{\text{HX}}$ on the radiation pattern is also analyzed. The analysis reveals that, as the angle is increased, the beam direction angle $\theta_{\text{max}}$, measured from the z-axis, increases. In other words, the beam direction in the elevation plane can be controlled by the helix pitch angle $\alpha_{\text{HX}}$.

3.2. Frequency response of the antenna characteristics

This subsection discusses the frequency response of the antenna characteristics around the test frequency $f_t = 12.225$ GHz. For this, $\alpha_{\text{HX}} = 8^\circ$ and $\phi_{\text{end}} = 1080^\circ$ are used as representative configuration parameters.

The angle $\theta_{\text{max}}$ of the tilted beam remains almost unchanged when the frequency is changed. The angle $\phi_{\max}$ varies within $95^\circ \pm 24^\circ$ over a frequency range of 11.7 GHz to 12.75 GHz (8.59 % bandwidth), as shown in Fig. 4. This variation in $\phi_{\max}$ is attributed to the phase relationship between the fields generated from the respective currents on the helical and spiral arms.

The frequency response of the axial ratio (AR) in the beam direction ($\theta_{\text{max}}, \phi_{\text{max}}$) is shown in Fig. 5. It is revealed that the AR within the analysis frequency range of 11.5 GHz to 13.0 GHz is small (less than 3 dB, desirable for CP radiation). Further analysis reveals that, within the same analysis frequency range, the resistive and reactive components of the input impedance have approximately $R_{\text{in}} = 100$ ohms and $X_{\text{in}} = 0$ ohms, respectively.

4. CHES Array

The radiation characteristics of a CHES that has configuration parameters $(r_{\text{HX}}, \phi_{\text{end}}, \alpha_{\text{HX}}) = (0.28$ wavelength, 1080°, 8°) are revealed in section 3. This section investigates an array antenna shown in Fig. 6, where N CHESs are used. Each CHES is rotated by the same angle (5 degrees, based on the results shown in Fig. 4) so that the maximum radiation is directed toward the positive-y space. Table 1 summarizes the gain of the CHES array, where the spacing $d_x$ is selected to be $0.8\lambda_{12.225}$. It is found that a gain of 25.2 dBi is obtained for N = 32. The tilted radiation pattern for N = 32 is presented in Fig.7.

5. Conclusions

An antenna composed of helical and spiral arms, designated as the CHES, is proposed as a small radiation element that can radiate a tilted CP beam. The diameter of this antenna is reduced to 77% of that of a conventional spiral antenna radiating a tilted CP beam.

The analysis of the CHES is performed under the conditions that the helix radius is $r_{\text{HX}} = 0.28$ wavelength and the number of helical turns is one, which contributes to realizing a low-profile antenna. It is found that, as the end angle $\phi_{\text{end}}$ of the spiral located above the helix is increased, the axial ratio for the tilted beam is improved. Note that this increase in the end angle $\phi_{\text{end}}$ does not affect the antenna height. It is also found that a change in the helix pitch angle $\alpha_{\text{HX}}$ results in a change in the beam direction $\theta_{\text{max}}$ in the elevation plane; as $\alpha_{\text{HX}}$ is increased, $\theta_{\text{max}}$ increases.

The analysis of the frequency response of the CHES shows a good axial ratio over a wide frequency range (11.5 GHz to 13.0 GHz) in the tilted beam direction ($\theta_{\text{max}}, \phi_{\text{max}}$). In addition to the
analysis of the CHES, an array composed of N CHES elements is analyzed and the gain as a function of N is calculated. It is found that a gain of 25.2 dBi is obtained for N = 32.

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References


Fig. 1 Conventional elements for tilted beam radiation

Fig. 2 Proposed composite structure of helical and spiral arms

Fig. 3 Radiation pattern of the CHES at 12.225 GHz.
Table. 1 Gain at 12.225 GHz.

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Fig. 6 Array composed of N CHESs

Fig. 7 Radiation pattern for a CHES array antenna at 12.225 GHz.