Design Method of a Circularly-Polarized Antenna Using Fabry-Pérot Cavity Structure

Jeongho Ju, Dongho Kim, Wangjoo Lee, and Jaeick Choi

A Fabry-Pérot cavity (FPC) antenna producing both high-gain and circularly-polarized (CP) behavior is proposed. To increase antenna gain and obtain CP characteristics, a superstrate composed of square patches with a pair of truncated corners is placed above the linearly polarized patch antenna with an approximately half-wavelength distance from the ground plane at the operating frequency. The proposed antenna has the advantages of high gain, a simple design, and an excellent boresight axial ratio over the operating frequency bandwidth. Moreover, used in an FPC antenna, the proposed superstrate converts a linear polarization produced by a patch antenna into a circular polarization. In addition, the cavity antenna produces left-hand circular-polarization and right-hand circular-polarization when a patch antenna inside the cavity generates *x*-direction and *y*-direction polarization, respectively. The measured and simulated results verify the performance of the antenna.

Keywords: High gain, circularly polarized, superstrate.

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I. Introduction

Over the past few decades, several studies have been made on high-gain circularly-polarized (CP) antennas, which are used for wireless communication and broadcasting systems, such as satellites and radar, wireless local area networks (WLANs), and so on. In order to increase the antenna gain, array antennas are widely used [1]-[3]. However, designing an array antenna is a complex process due to the complicated feeding networks needed to generate both the CP behavior and high gain, and such networks cause low efficiency in high-gain antennas.

As another approach to obtain high-gain behavior, electromagnetic band gap (EBG) resonator antennas, Fabry-Pérot cavity (FPC) antennas have also been proposed [4]-[7].

Recently, the properties of metamaterials have been analyzed both theoretically and experimentally [8]-[10]. Some researchers have developed high-directivity antennas with the metamaterial superstrate having a zero or low refractive index [11]-[13]. These antennas provide high gain with a simple feeding structure. Although such high-gain antennas are easily designed without complicated feeding networks, a CP source antenna is needed to produce the CP in cavity antennas. A high-gain CP antenna based on an EBG resonator has been developed [14], [15]. It is possible to design a high-gain CP antenna using EBG resonator antennas with the CP source in the cavity. However, design methods of CP antennas are relatively complex compared to that of linearly polarized (LP) antennas since a position of feeding points and shapes of antennas should be optimized in order to obtain a CP.

In this paper, we present a high-gain CP antenna for WLAN (5.15 GHz to 5.35 GHz), which is based on an FPC structure using a simple LP patch antenna for signal feeding into the cavity. The proposed antenna shows both high-gain and CP behavior around the resonant frequency. The proposed antenna is composed of a ground plane, an LP patch antenna, and a superstrate working as a polarizer to convert an LP antenna into a CP antenna. Furthermore, the proposed antenna provides both left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) according to the linear polarizations generated by the patch antenna inside the cavity. Compared to a conventional CP array antenna, the proposed antenna has such advantages as high efficiency, simple feeding networks, and an easily controlled CP-type antenna depending on the linear polarization of the source antenna.

Consequently, we can design a high-gain CP antenna using an FPC structure with a simple LP patch antenna. To demonstrate our design method, all simulations are performed using CST Microwave Studio. Good agreement between the predicted and measured data shows the validity and usefulness of our design approach.

II. Analysis and Measured Results

A photograph of the fabricated antenna and the geometry of the unit cell used in the superstrate are shown in Fig. 1. The separation between the superstrate and ground plane is 29.8 mm, which corresponds to approximately a half-wavelength to enhance the gain at the operating frequency.

For the unit cell of the superstrate, a square patch with a pair of truncated corners used to produce the circular polarization is printed on the upper side of a dielectric laminate with a thickness of 1.57 mm and dielectric constant of $\varepsilon_r = 3.5$. The superstrate consists of a 7×7 truncated patch array. For signal feeding into the cavity, a rectangular patch antenna is printed on a 1.52-mm-thick dielectric substrate of $\varepsilon_r = 3$.

To predict the CP behavior of the FPC antenna, multiple reflection effects in the cavity are considered, and all of the

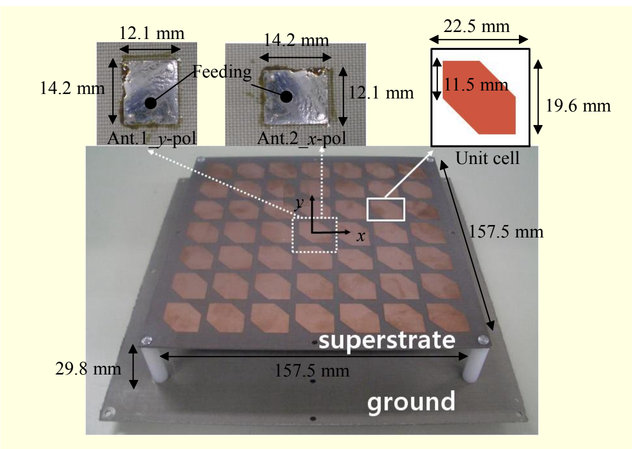

Fig. 1. Geometry of the proposed antenna.

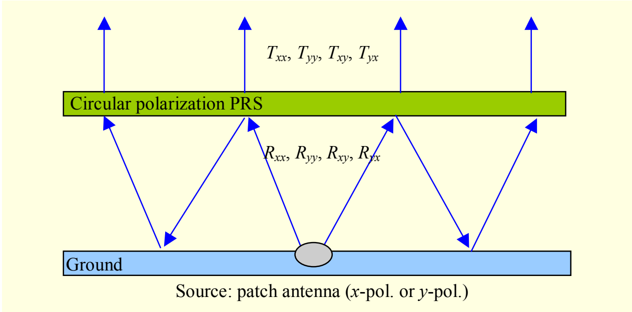

Fig. 2. Multiple reflections and transmissions between PRS and ground plane.

fields passing through the superstrate are then calculated. The proposed antenna is analyzed using both reflection and transmission coefficients of the superstrate, and the reflection coefficients of the ground plane, for a normal incidence wave, which is given by (see [16])

$$
\begin{aligned}
& a_1 = e^{-j\phi} : x\text{-pol.} \quad \text{or} \quad b_1 = e^{-j\phi} : y\text{-pol.} \\
& a_{n+1} = e^{-j2\phi} e^{j\pi} (R_{xx} a_n + R_{xy} b_n), \\
& b_{n+1} = e^{-j2\phi} e^{j\pi} (R_{yy} b_n + R_{yx} a_n), \\
& E_x = \sum_{n=1}^{\infty} (T_{xx} a_{n+1} + T_{xy} b_{n+1}), \\
& E_y = \sum_{n=1}^{\infty} (T_{yy} b_{n+1} + T_{yx} a_{n+1}),
\end{aligned}
\tag{1}
$$

where ϕ is the electrical length between the ground plane and superstrate, n indicates the repetition numbers of the reflection wave inside the cavity, π is the refection phase of the ground, and R and T are the reflection and transmission coefficients of the superstrate, respectively. Also, the subscripts for both R and T denote the polarization of fields in order to describe the field transition of the reflection and transmission. For example, T_{xy} indicates the quantity of field conversion from y-polarization to x-polarization for transmission coefficients passing through the superstrate. When x-pol. is excited in the cavity, the initial value of b_1 is set at 0. On the other hand, a_1 becomes 0 when y-pol. is excited.

Figure 2 shows the multiple reflections and transmission of the cavity in order to demonstrate the concept of our proposed method. To produce a circular polarization, the two field components (E_y, E_x) must have the same magnitude and be ±90° out of phase; namely, the ratio of E_y to E_x is $1\angle \pm 90^\circ = \pm j$, where $+j$ is for LHCP and $-j$ is for RHCP.

To obtain the reflection and transmission coefficients of the superstrate, the plane waves are illuminated from wave port 1 (to the ground) with x-polarization or y-polarization to wave port 2 (beyond the superstrate) in the z-direction, as shown in Fig 3. Also, all the lateral sides of the unit cell are enclosed with

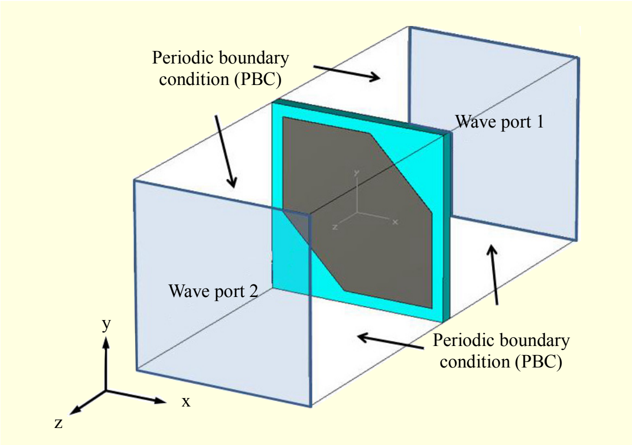

Fig. 3. Geometry of unit cell and its boundary conditions.

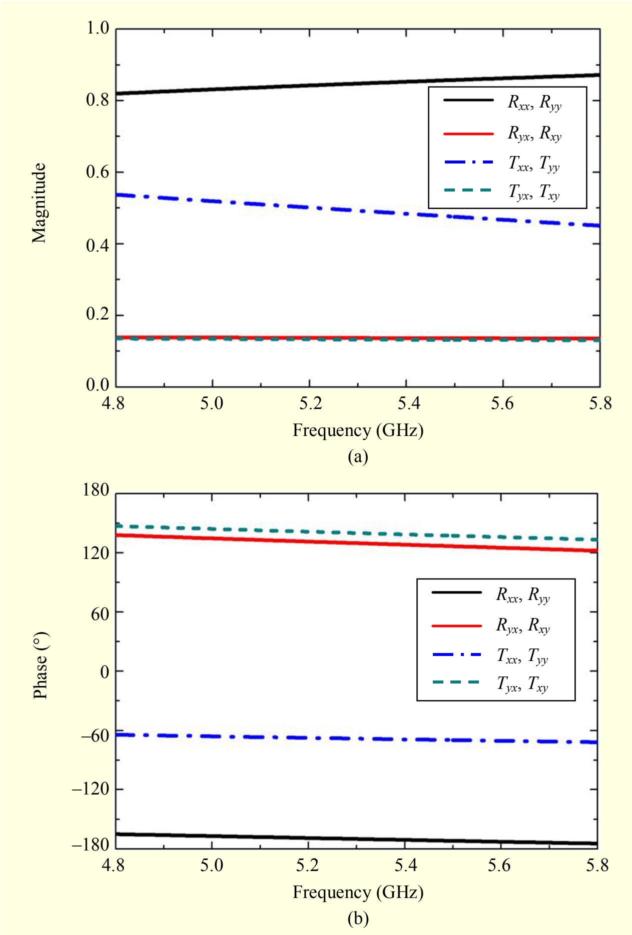

Fig. 4. Reflection and transmission coefficients of unit cell: (a) magnitudes and (b) phases.

a periodic boundary condition (PBC). The unit cell analysis method not only reduces the calculation time, but also precisely predicts the reflection and transmission coefficients compared to treating the entire superstrate structure.

Because the proposed unit cell is symmetric with respect to the *x*-polarizations and *y*-polarizations of the incident wave, the reflection and transmission coefficients, which are computed in Fig. 4, are identical to each other.

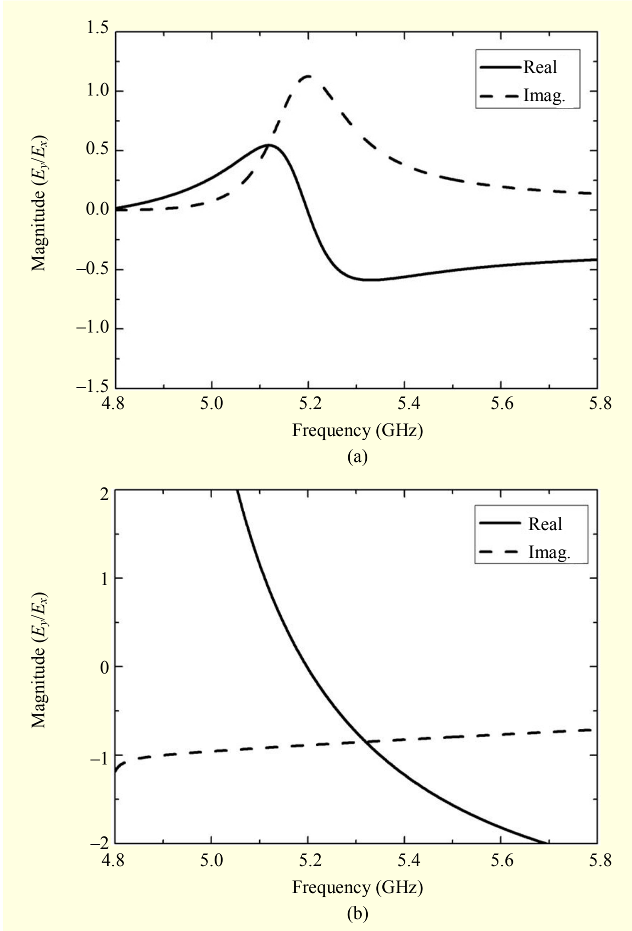

Fig. 5. Magnitudes of real and imaginary parts of E_y/E_x according to linear polarization type of source antenna: (a) *x*-pol.→LHCP and (b) *y*-pol.→RHCP.

Figure 5 shows the magnitudes of the real and imaginary parts of (E_y/E_x) according to the polarization of the source antenna, where the proposed antenna is operating at 5.2 GHz with a fixed distance of 29.8 mm between the ground and superstrate. The real and imaginary values of (E_y/E_x) are calculated with (1) using simulated coefficients of the unit cell, as shown in Fig 4. As previously stated, the CP characteristics are determined by the two field components (E_x, E_y) since $+j$ and $-j$ indicate LHCP and RHCP, respectively. We can easily obtain the axial ratios from the magnitudes of (E_y/E_x). Figure 5(a) shows the RHCP characteristics at 5.2 GHz since (E_y/E_x) is $j1.07$. In contrast with the RHCP case shown in Fig. 5(a), Fig. 5(b) demonstrates the LHCP characteristics at 5.2 GHz since (E_y, E_x) is $-j0.93$.

Consequently, an LHCP antenna is realized when the *x*-polarization patch antenna is located inside the cavity, and an

Table 1. Calculated axial ratios.

Distance (mm)	Pol. of source	CP type	Oper. freq. (GHz)	Axial ratio (dB)	E_y/E_x
29.8	*x*-pol.	LHCP	5.2	1.17	$j1.12$
	y-pol.	RHCP	5.2	1.17	$-j0.88$
30.8	*x*-pol.	LHCP	5.05	0.67	$j1.07$
	y-pol.	RHCP	5.05	0.67	$-j0.93$

RHCP antenna is achieved by placing a *y*-polarization antenna inside the cavity. Also, the axial ratio is calculated from (1), which is given by (see [16]):

$$AR=\frac{[\frac{1}{2}\{|E_x|^2+|E_y|^2+[|E_x|^4+|E_y|^4+2|E_x|^2|E_y|^2\cos(2\phi)]^{1/2}\}]^{1/2}}{[\frac{1}{2}\{|E_x|^2+|E_y|^2-[|E_x|^4+|E_y|^4+2|E_x|^2|E_y|^2\cos(2\phi)]^{1/2}\}]^{1/2}}, \quad (2)$$

where $\phi=\angle Ex-\angle Ey$.

Table 1 indicates the axial ratios according to distance variances between the superstrate and ground. The axial ratios are predicted from (2) as a consequence of the polarizations of the source placed inside cavity. Axial ratios of the LHCP and the RHCP are simultaneously smaller than 3 dB at the operating frequencies of 5.05 GHz and 5.2 GHz when the distances between the superstrate and ground are 30.8 mm and 29.8 mm, respectively.

Therefore, the proposed antenna is quite adequate for a high-gain CP antenna, and the operating frequencies of the CP antenna are controlled by the height of the cavity. Owing to the symmetry of the unit cell for an *x*-polarization and *y*-polarization of an incident wave, the magnitude of axial ratios of the LHCP and RHCP antennas are identical.

To certify the validity of our design method, we compared the measured and simulated results. A comparison of the measured and simulated gains is given in Fig. 6. Figure 6 shows that the gains of the proposed RHCP and LHCP high-gain antennas, and the circular polarization property of the proposed antenna, are changed by the linear polarization type (*x*-polarized or *y*-polarized) of the patch antenna inside the cavity. A maximum gain value of 16.3 dB at 5.2 GHz has been measured over a 1 dB bandwidth of about 4.2% (5.05 GHz to 5.27 GHz) for both the RHCP and LHCP antennas. The simulated and measured results are in good agreement. It is worth noting that the proposed antenna simultaneously produces high-gain and CP behavior by using a simple LP patch antenna. Both gain curves for LHCP and RHCP antennas are nearly identical, owing to the symmetry of the superstrate for *x*-polarization and *y*-polarization of the incident wave.

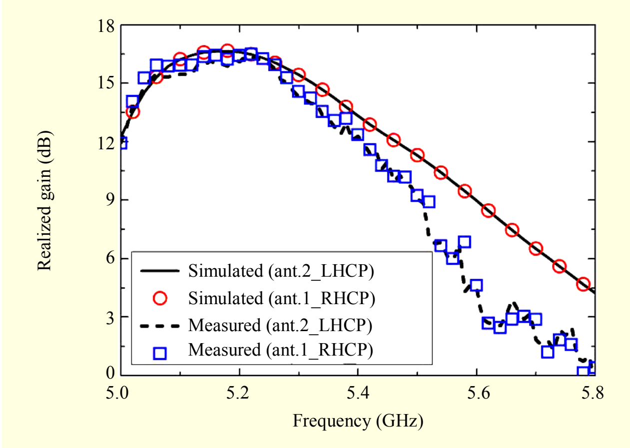

Fig. 6. Measured and simulated gains for proposed antenna.

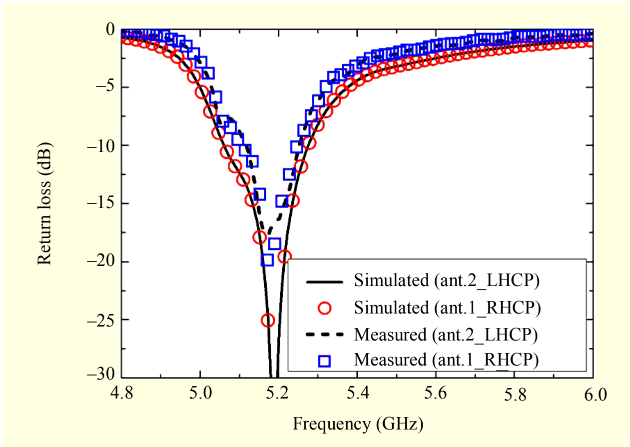

Fig. 7. Measured and simulated return losses for proposed antenna.

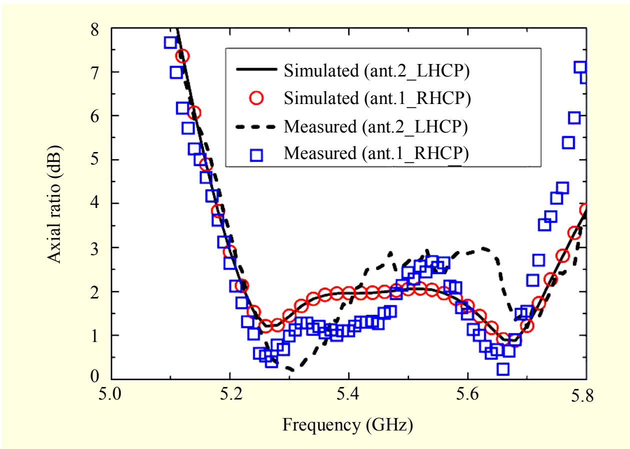

Fig. 8. Measured and simulated boresight axial ratios for the proposed antenna.

The return loss of the proposed antenna is shown in Fig. 7. The measured –10 dB bandwidth for both the RHCP and LHCP antennas is about 4.1% (5.06 GHz to 5.27 GHz). The measured return loss values of lower than –10 dB exactly

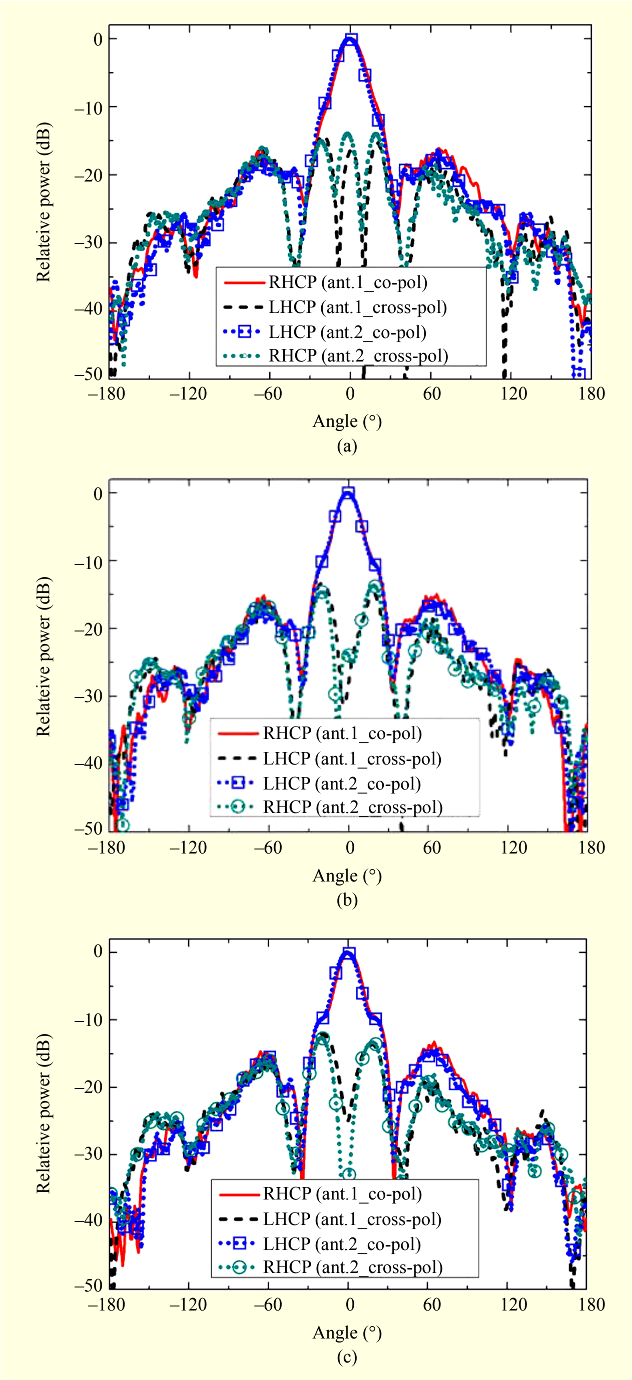

Fig. 9. Measured radiation patterns: (a) 5.2 GHz, (b) 5.25 GHz, and (c) 5.3 GHz.

correspond to the 1 dB frequency bandwidth, as shown in Fig. 6. There is a small difference of –10 dB bandwidth in the return loss compared to simulated results, but otherwise the simulated and measured results agree well with each other.

The measured boresight axial ratios of the proposed antenna are plotted as a function of frequency in Fig. 8, and the measured and simulated results are compared. The measured and simulated axial ratio curves have a small difference in amplitude over the frequency band of the 3 dB axial ratio, but otherwise the simulated and measured results agree well with each other. The measured 3 dB axial ratio bandwidths for the RHCP and LHCP antennas are 9.5% (5.2 GHz to 5.72 GHz) and 10.3% (5.21 GHz to 5.78 GHz), respectively.

Measured radiation patterns in the shape of a pencil beam at 5.25 GHz, 5.25 GHz, and 5.3 GHz for the ϕ=0° plane are shown in Fig. 9. Radiation patterns for the RHCP and LHCP antennas resemble each other. The measured sidelobe is –15 dB for the RHCP antenna and –16.1 dB for the LHCP antenna at 5.25 GHz. Also, the cross-polarizations are lower than 30 dB compared to the co-polarizations for both the RHCP and LHCP antennas at 5.25 GHz. The total efficiency is about 95%, and the front-to-back ratio (FBR) is more than 35 dB in both the RHCP and LHCP antennas at 5.25 GHz.

Therefore, the proposed antenna is quite adequate for a high-gain CP antenna. In addition, the proposed antenna can be utilized in a dual CP antenna by exiting the *x*-polarization and *y*-polarization waves in the cavity.

III. Conclusion

We proposed a Fabry-Pérot cavity (FPC) antenna for a high-gain CP antenna. With the help of the superstrate converting linear polarization into circular polarization, our proposed antenna provides both high gain and CP characteristics.

To achieve LHCP and RHCP behavior in the proposed antenna, *x*-polarized and *y*-polarized plane waves are generated inside the cavity, respectively. The circular polarization type of the proposed antenna is varied by the linear polarization type generated by the patch antenna inside the cavity.

In addition, using the newly proposed prediction method to estimate the CP behaviors, a high-gain CP antenna is designed simply. Good agreement between the measured and theoretically predicted behavior ensures the validity of our design and prediction method.

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